GEOTHERMAL RESOURCES
OF
YELLOWSTONE NATIONAL PARK
1993–1995

by
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Yellowstone Center for Resources
National Park Service
Yellowstone National Park, Wyoming

1997

YCR-NR-97-2

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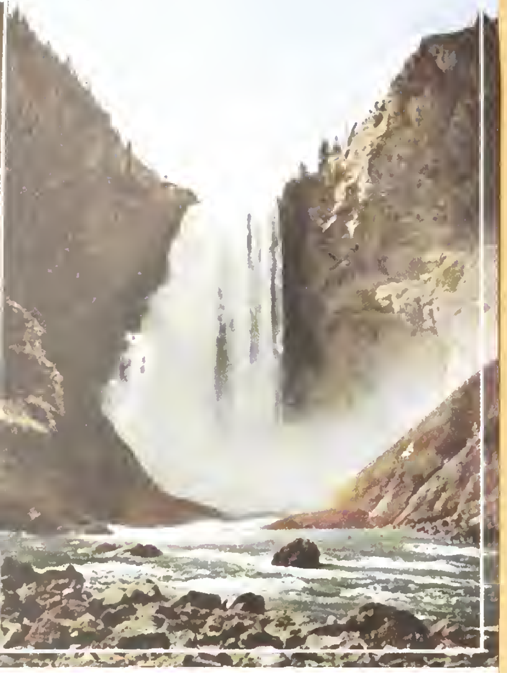

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TABLE OF CONTENTS

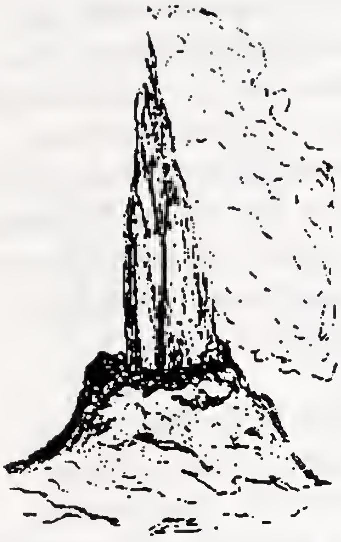
Upper Geyser Basin Geyser Activity—1995: Exploratatory Analysis and Summary 1
  Plume Geyser 1
  Castle Geyser 6
  Oblong Geyser 9
  Riverside Geyser 12
  Grand Geyser 15
  Daisy Geyser 18

Daisy Geyser : 1994–1995 23

Grand Geyser: 1993–1995 29

Spouter Geyser: Summary and Report of Initial Investigation 35

Norris Geyser Basin: Echinus and Monarch Geyser Summaries 47
  Echinus Geyser 47
  Monarch Geyser 51



UPPER GEYSER BASIN GEYSER ACTIVITY—1995: EXPLORATORY ANALYSIS AND SUMMARY

INTRODUCTION

This report is an exploratory analysis and summary of geyser activity in the Upper Geyser Basin during the year 1995. Some comparison with prior years is discussed. More in-depth comparisons will be presented in a future report.

The majority of times of eruptions of geysers are the result of electronic monitoring. With the exception of Riverside Geyser, *Ryan Instruments* temperature probes were deployed at Plume, Daisy, Castle, Grand, and Oblong geysers. Much of the Riverside Geyser data was obtained through instruments deployed by the Carnegie Institute. In addition to electronic monitoring, actual observances of eruptions recorded in the Old Faithful Logbook supplement the eruptions recorded with instrumentation. In this report, all intervals of time between the beginning of one eruption and the beginning of a following eruption will be denoted as IBE. All IBE are in minutes.

PLUME GEYSER

Between 3/31/95 and 12/11/95, 7304 IBE were determined. This does not represent all eruptions of Plume; some gaps are present in the data record. However, this data represents the longest and most detailed record of IBE recorded to date.

Figure P1 is a histogram of the distribution of IBE. Included in the figure are summary statistics describing the distribution.

Figures P2 and P3 are the series of median and mean daily IBE, respectively. Both figures clearly show that longer IBE occur prior to 5/01/95. There are several possible explanations for the longer IBE. They could be the result of instability of Plume due to an eruption of Giantess Geyser in January of 1995; past eruptions of Giantess generally have led to a temporary reduction in Plume IBE, followed by an increase in Plume IBE. It is possible that prior to May 1995, Plume had not recovered from the Giantess eruption. From May through mid-August, Plume IBE is quite stable, staying well within the first and second quartiles of 36 and 41 minutes (see Figure P1).

A swarm of local earthquakes in early July appears to have had little influence on Plume. In mid-August, Giantess began to show sign of activity in the form of large boils and slight overflow. The effect of this activity on Plume IBE is present throughout early November. Giantess erupted again on 11/09/95. At this time Plume was not being monitored and there is a gap in the series. Monitoring of Plume resumed early in December and is highly suggestive of typical Plume activity following an eruption of Giantess: reduced IBE.

Figures P4 and P5 are series of Plume mean and median IBE during the hour of which eruptions occurred. Both figures are consistent with past studies suggesting that Plume exhibits reduced IBE during daylight hours and increased IBE during nighttime hours. No definitive explanation has yet been discovered for this phenomenon. It is possible that a warming of surface runoff due to solar radiation may contribute to the reduced IBE during daylight hours. A project will soon be implemented which will continuously monitor air temperature on Geyser Hill.

Figures P6 and P7 are seven-day running averages and seven-day running medians (median trace), respectively. The running averages and running medians tend to highlight the general changes in Plume IBE.

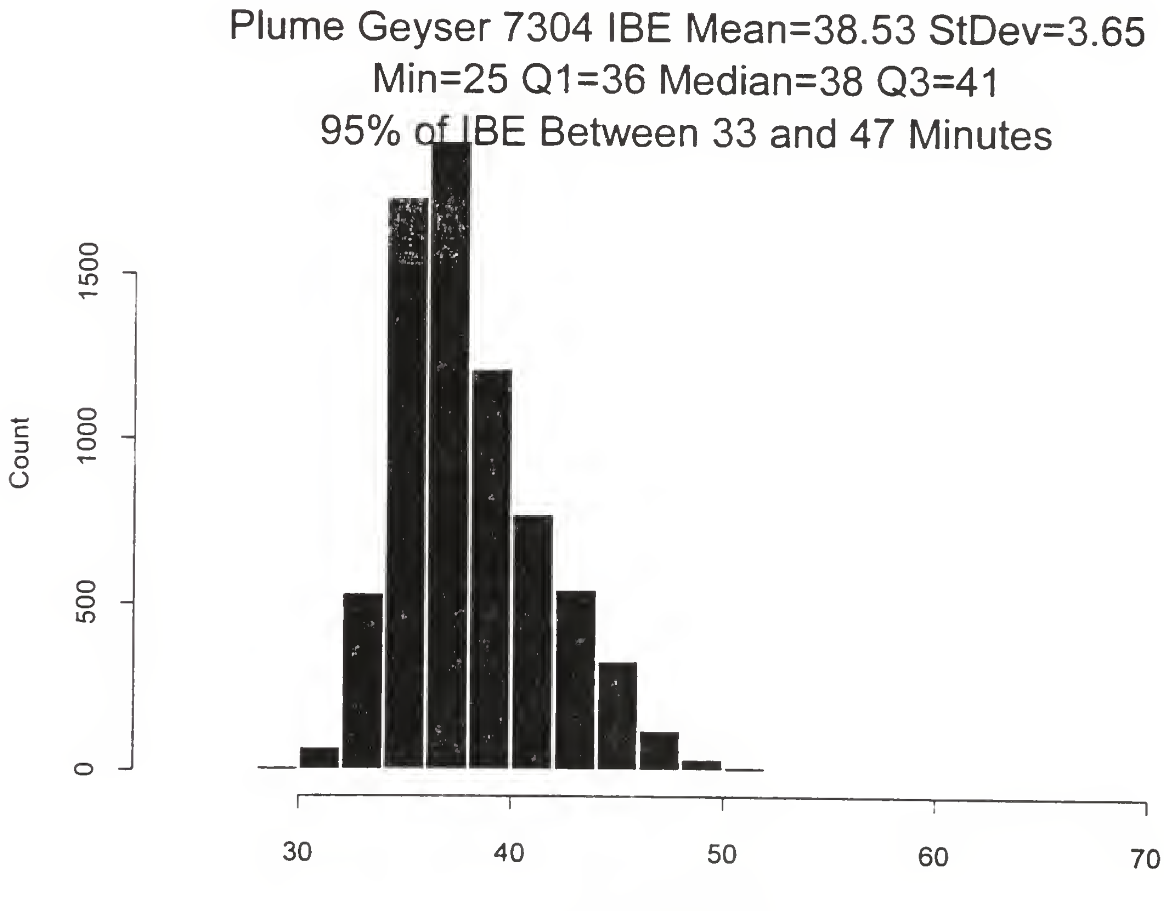
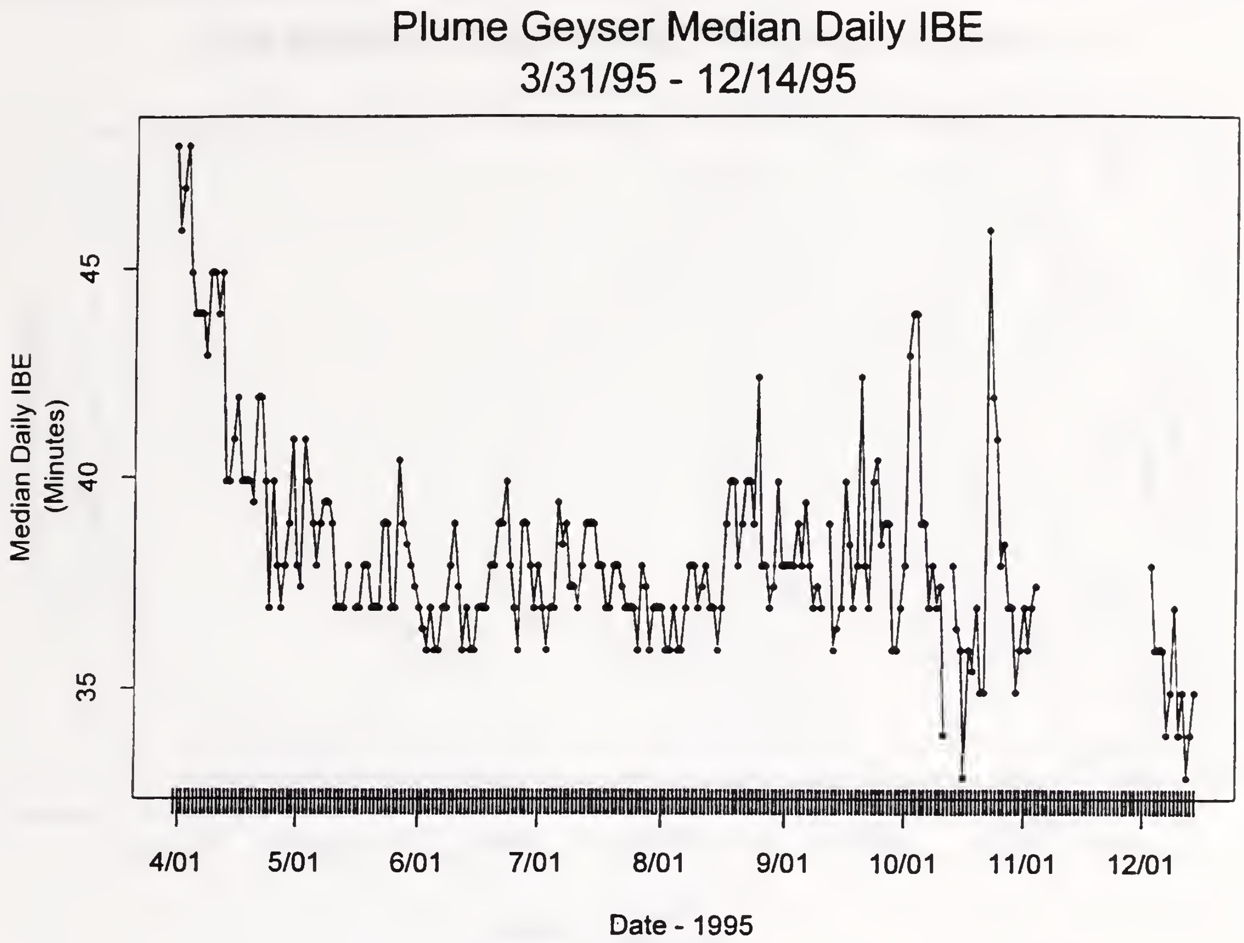
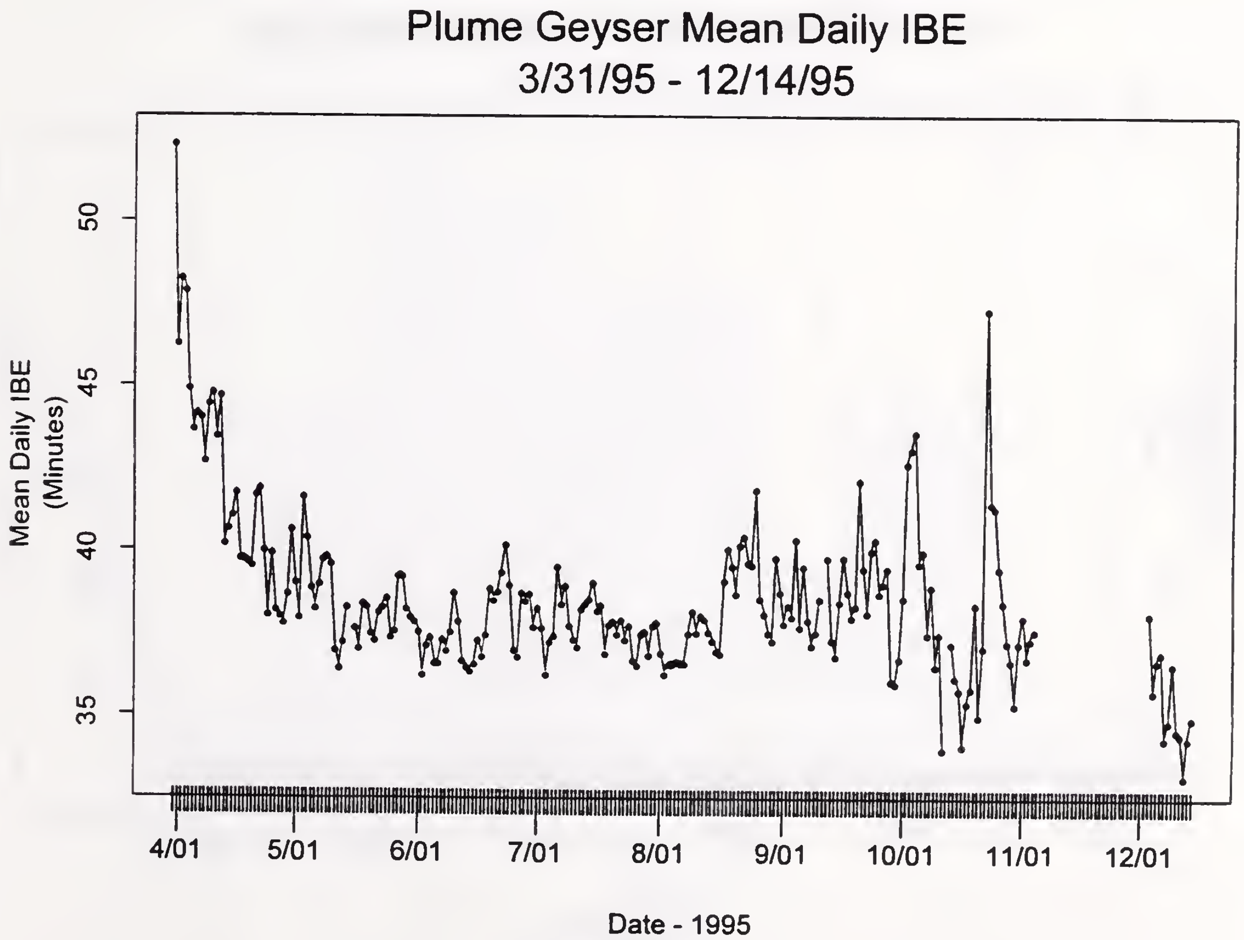


Figure P1



Plume Geyser Median Daily IBE
3/31/95 - 12/14/95

Figure P2



Plume Geyser Mean Daily IBE
3/31/95 - 12/14/95

Figure P3

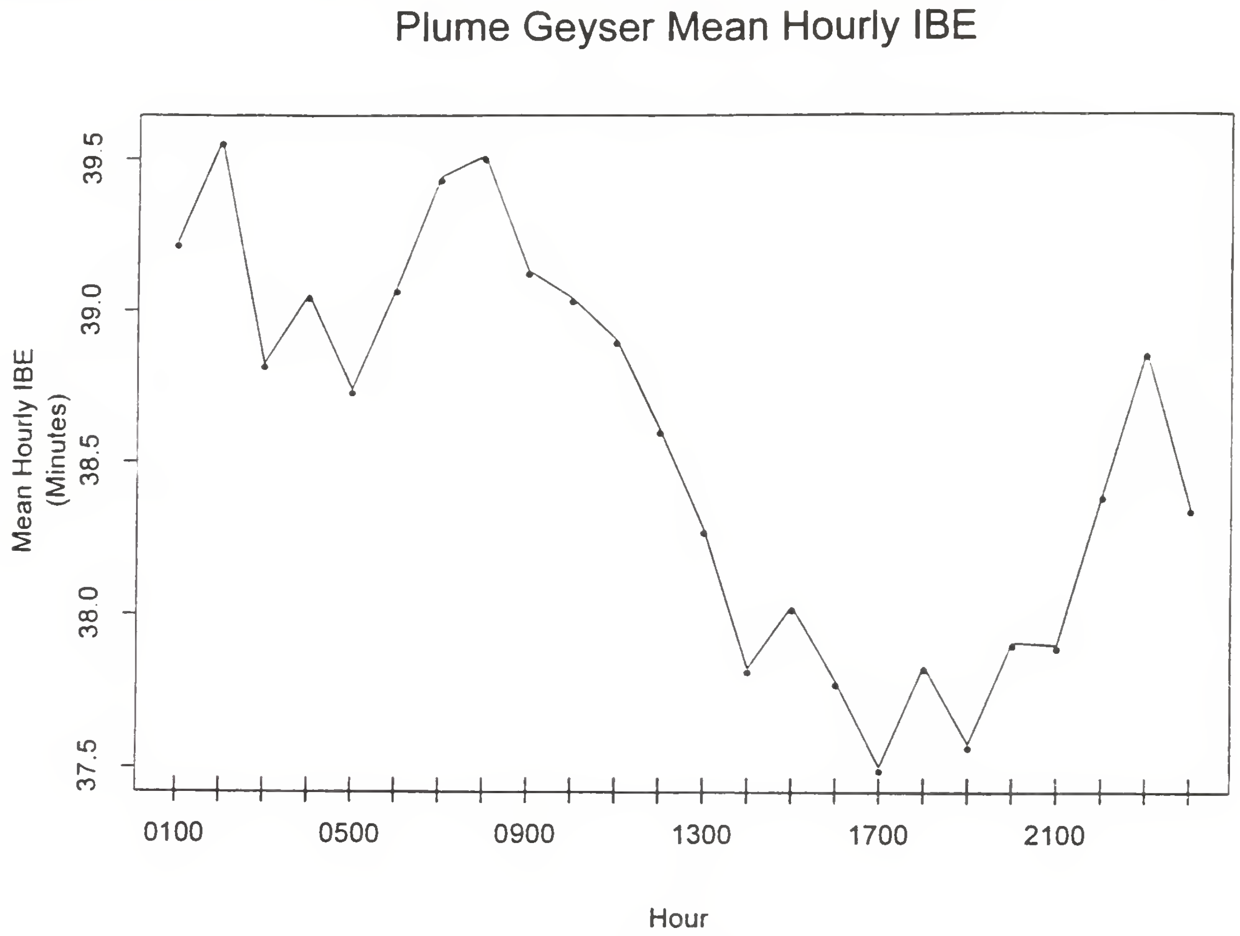


Figure P4

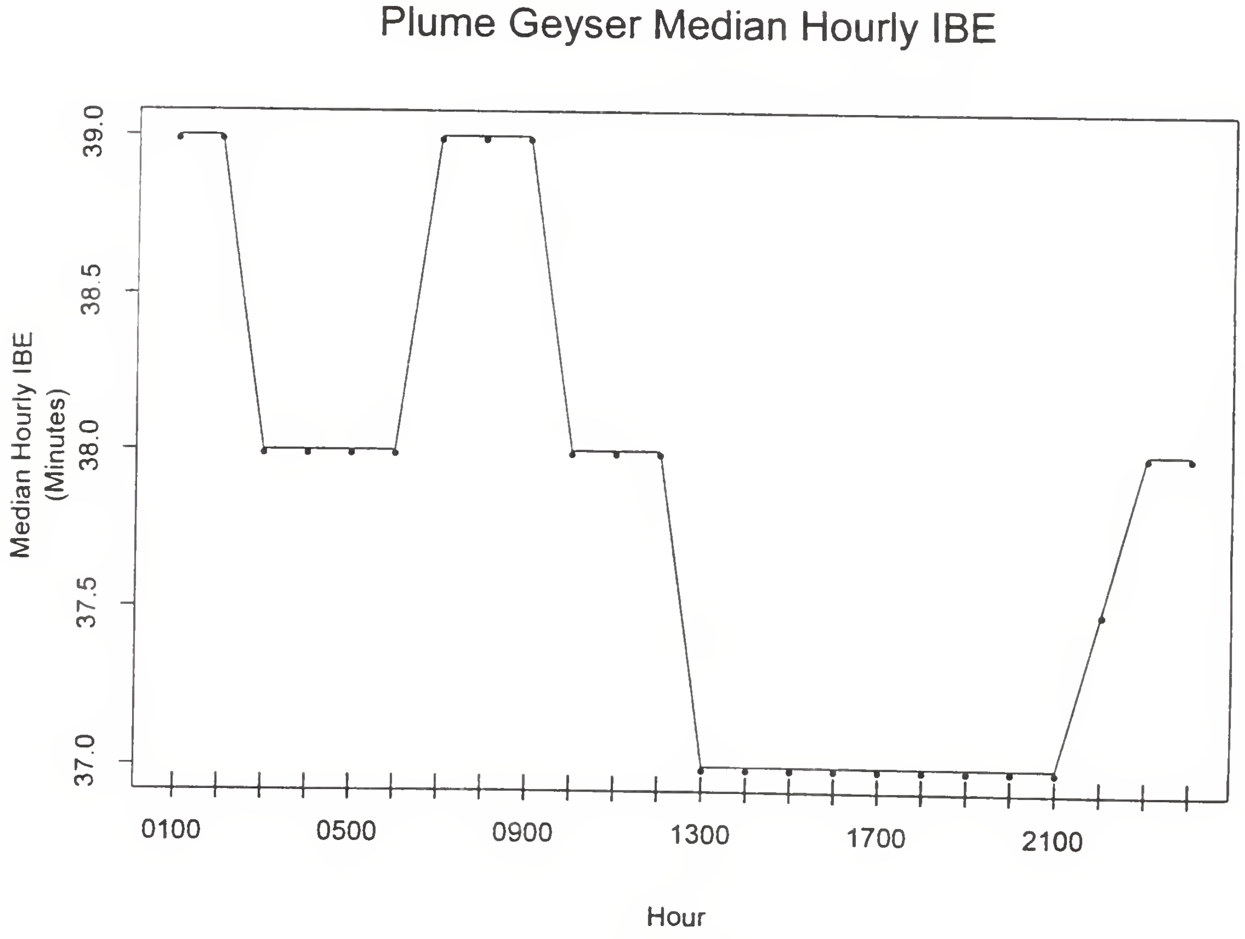


Figure P5

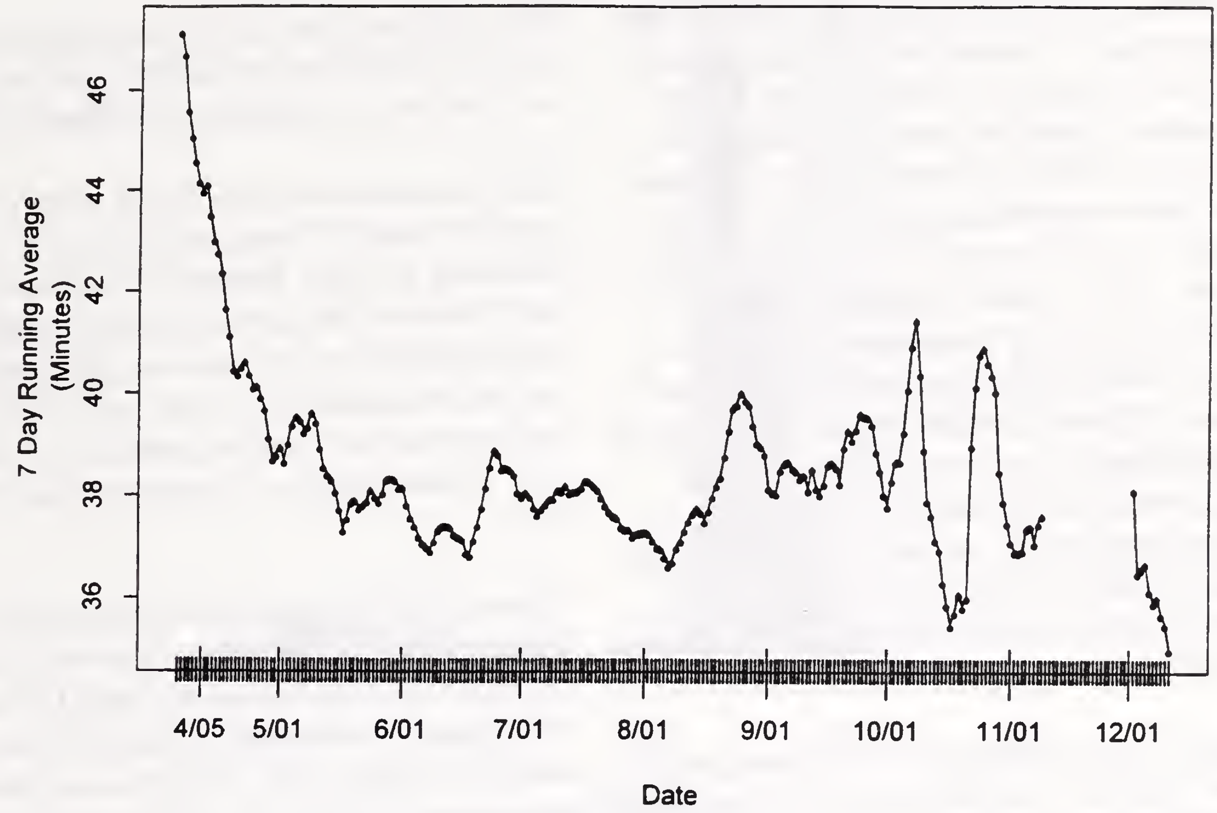

Plume Geyser 7 Day Running Averages
4/05/95 - 12/11/95

Figure P6

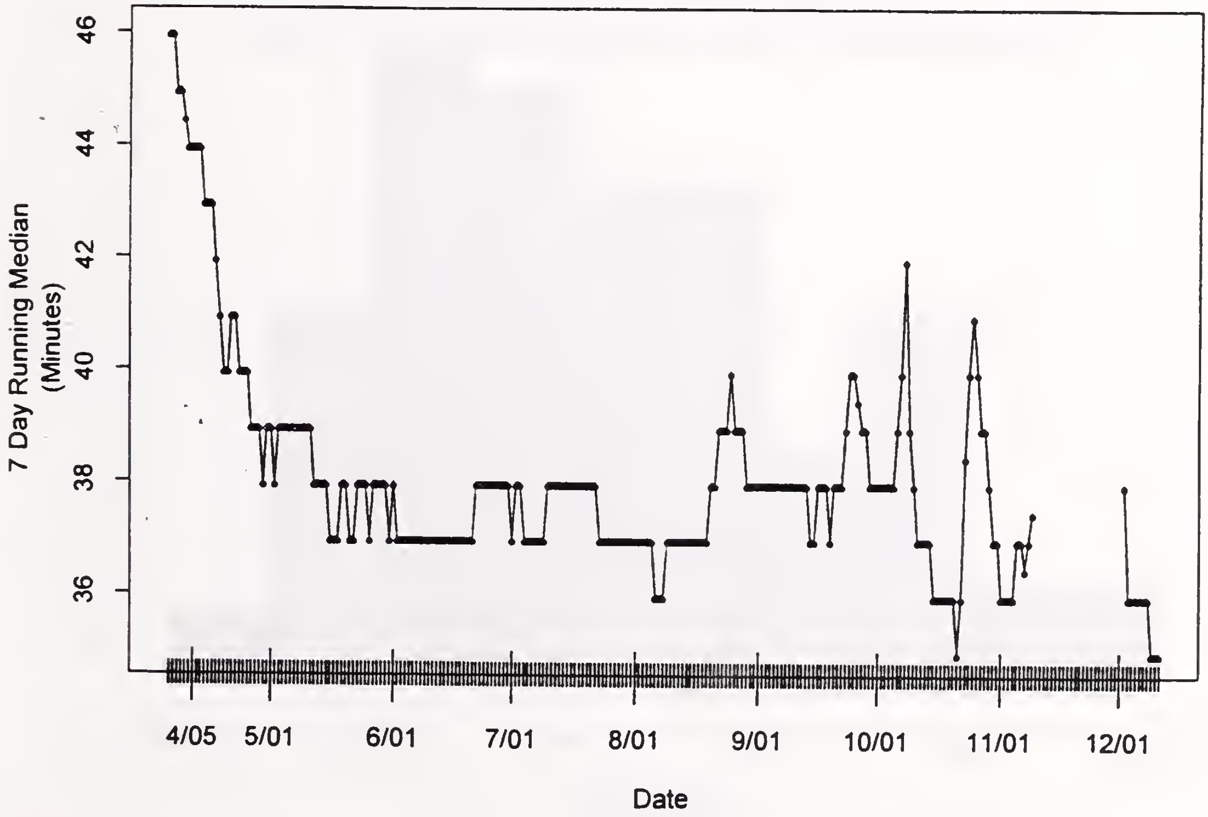

Plume Geyser 7 Day Running Medians
4/05/95 - 12/11/95

Figure P7

CASTLE GEYSER

Between 3/16/95 and 12/11/95, 506 IBE were determined. The eruption activity of Castle Geyser during 1995 included many *minor* eruptions: more than recorded/ observed in 1993 and 1994. (*Ed. note: Major eruptions last approximately an hour, with an initial water phase followed by a lengthy steam phase to the activity; minor eruptions typically display a series of intermittent splashes lacking a distinct subsequent steam phase.*) As a result, IBE due to *major* eruptions tended to be slightly longer than previous years. Many eruptions of Castle during 1995 included sloppy beginnings. An eruption would appear to begin only to abort after a minute or two. The eruption would then be delayed for as long as 9 minutes.

Figure C1A is a histogram of the distribution of all 506 IBE. The distribution clearly reflects the IBE due to both major and minor types of eruptions. The data was split into two types of IBE. IBE less than 600 minutes tend to be the result of minor activity and the distribution of such activity is represented in **Figure C1B**.

IBE greater than or equal to 600 minutes tend to be the result of major activity or recovery following a minor. **Figure C1C** reflects the distribution of this type of activity. In general, the median IBE of 697 minutes in Figure C1C is a fair representation of past years' IBE between majors, excluding minors and recovery. A future study will present an analysis of this.

Figure C2 is the series of consecutive IBE. Gaps represent missing data. It is clear from this series why predictions of Castle Geyser were generally suspended by the Old Faithful naturalists during 1995. With the exception of a short span of time from early August to late August, Castle Geyser fluctuated wildly between minor and major eruptive activity.

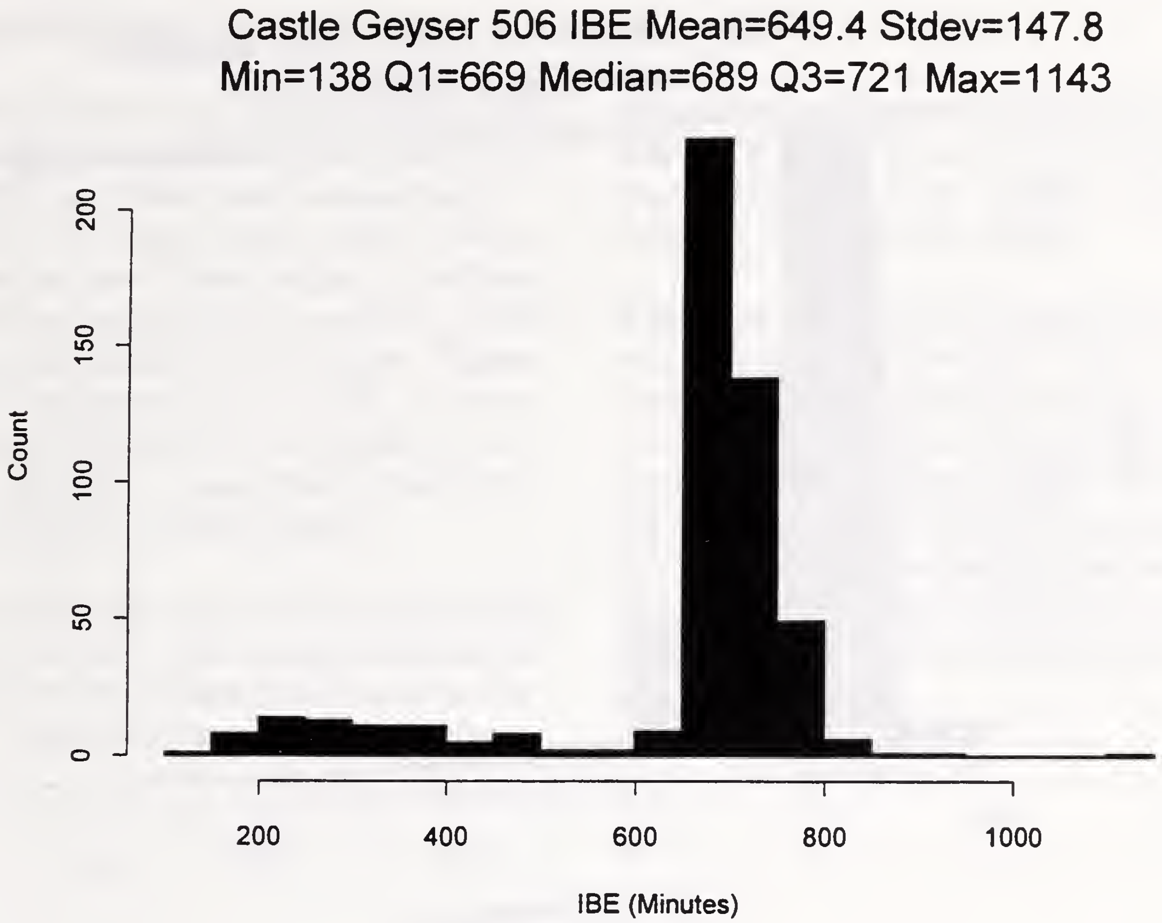


Figure C1A

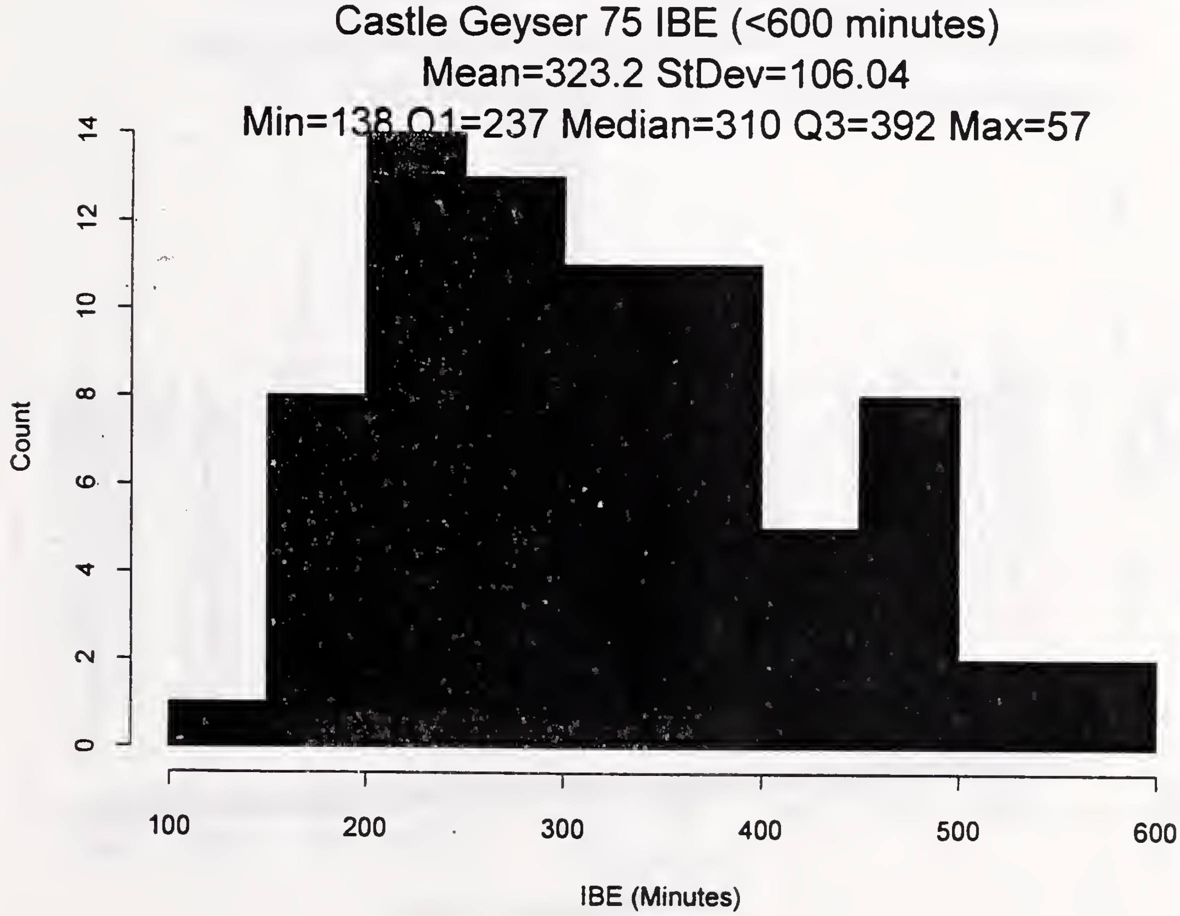
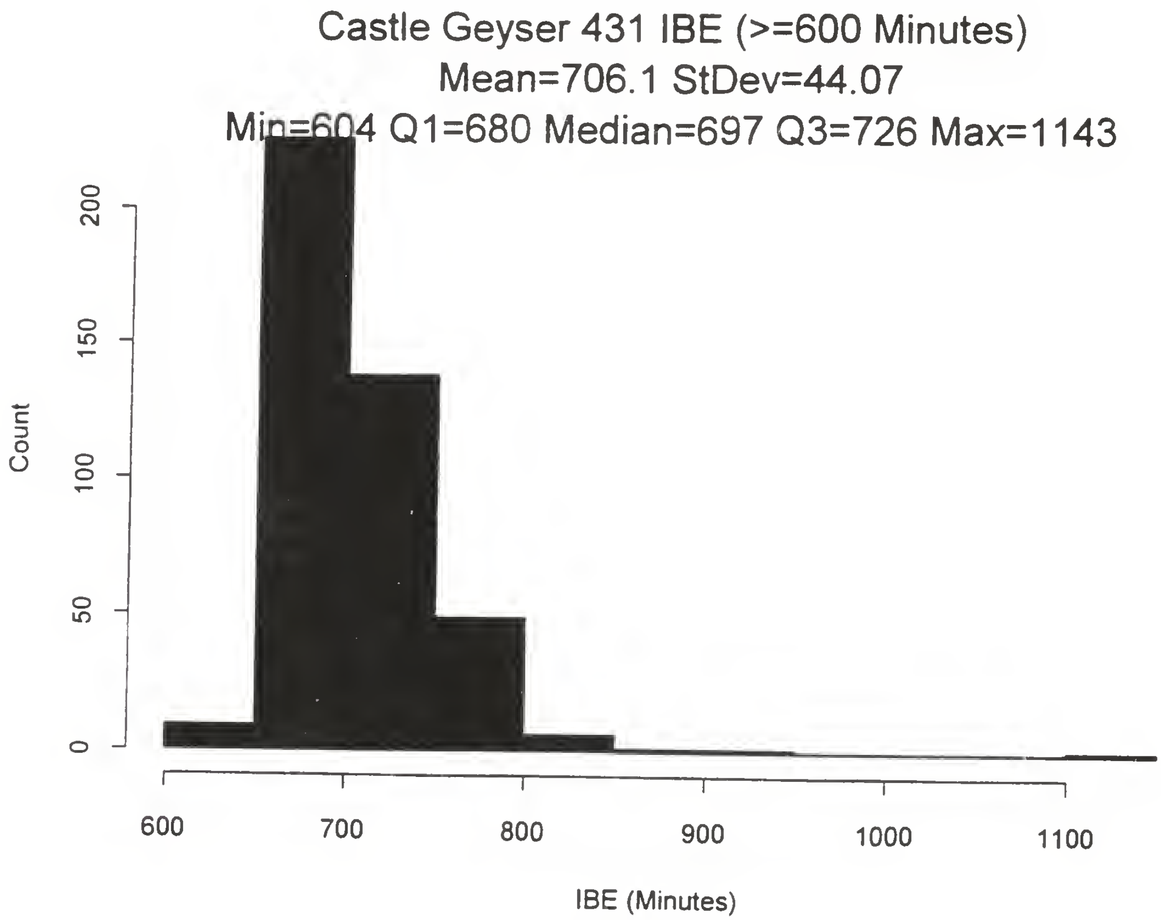
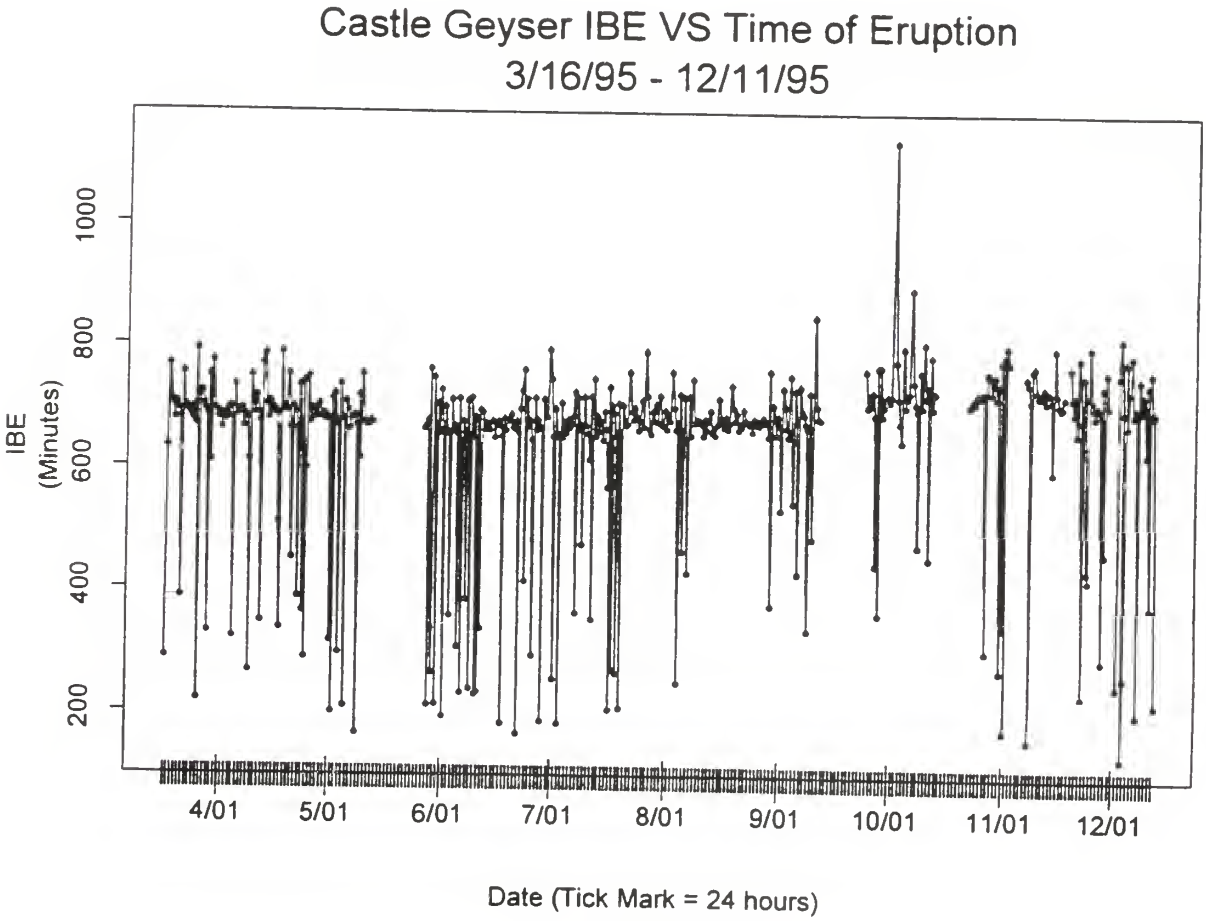


Figure C1B



Castle Geyser 431 IBE (>=600 Minutes)
Mean=706.1 StDev=44.07
Min=604 Q1=680 Median=697 Q3=726 Max=1143

Figure C1C



Castle Geyser IBE VS Time of Eruption
3/16/95 - 12/11/95

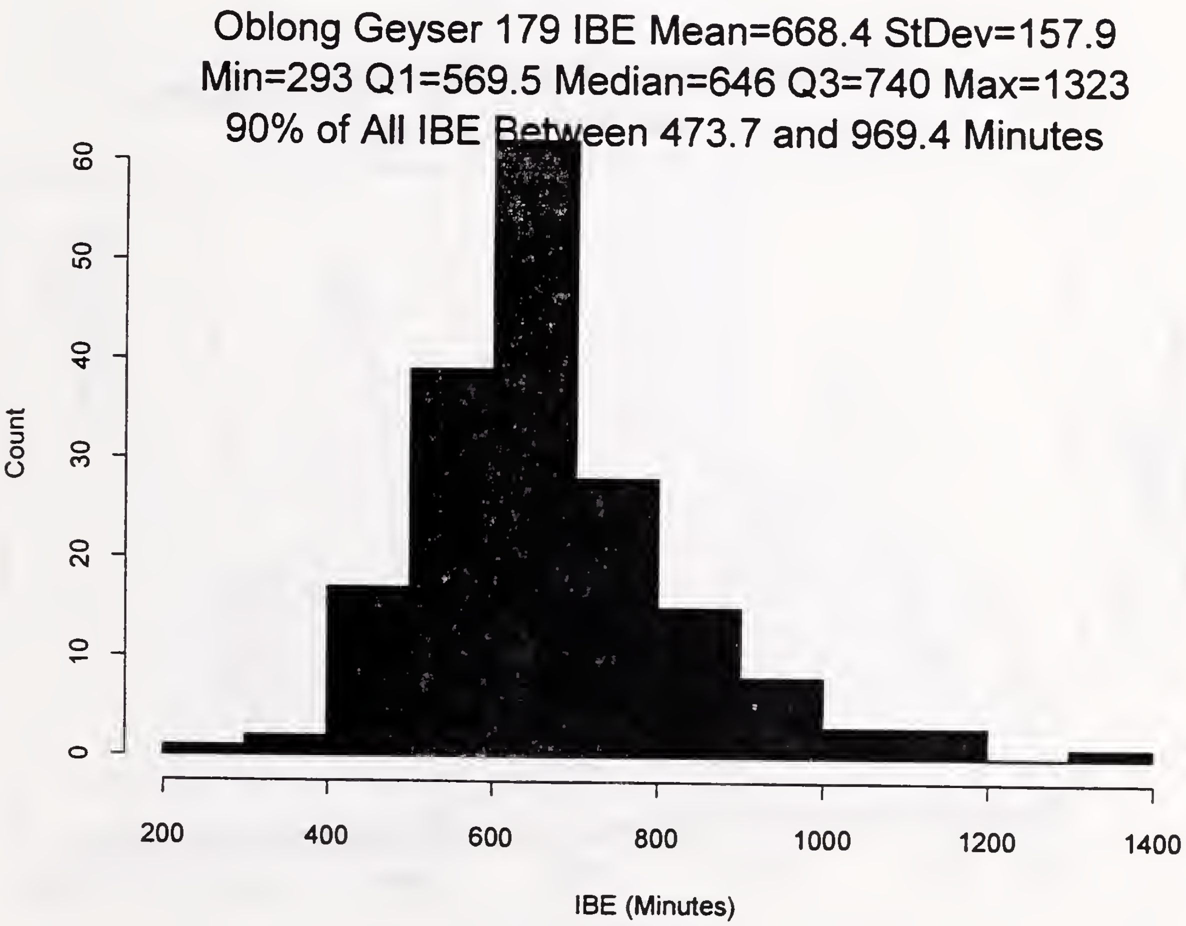
Figure C2

OBLONG GEYSER

Between 8/01/95 and 11/01/95, 179 IBE were obtained. Oblong began eruptive activity in late July; the precise date is undetermined. There is increasing evidence (1994-1995) that the activation of Oblong signals a significant buildup of energy which is eventually released during an eruption of Giant Geyser. **Figure O1** is a histogram of the 179 IBE. The large variance and range are due primarily to the large fluctuation upon activation and following an eruption of Giant Geyser.

Figure O2 is the series of IBE plotted against time of eruption. There is approximately one month of erratic behavior upon initial activation. Oblong IBE then remains relatively stable from approximately 8/30/95 until the eruption of Giant Geyser on 9/25/95. Following the eruption of Giant, Oblong's eruption pattern is once again very erratic.

Figure O3 and Figure O4 are seven-day running averages and medians of IBE, respectively. These smoothed series accentuate the series observed in Figure O2. In addition to supportive evidence of the jump in IBE following the Giant eruption, there is some evidence that immediately following the Giant eruption Oblong IBE temporarily drops. A review of the series in Figure O2, shows that this is indeed the case.



Oblong Geyser 179 IBE Mean=668.4 StDev=157.9
Min=293 Q1=569.5 Median=646 Q3=740 Max=1323
90% of All IBE Between 473.7 and 969.4 Minutes

Figure O1

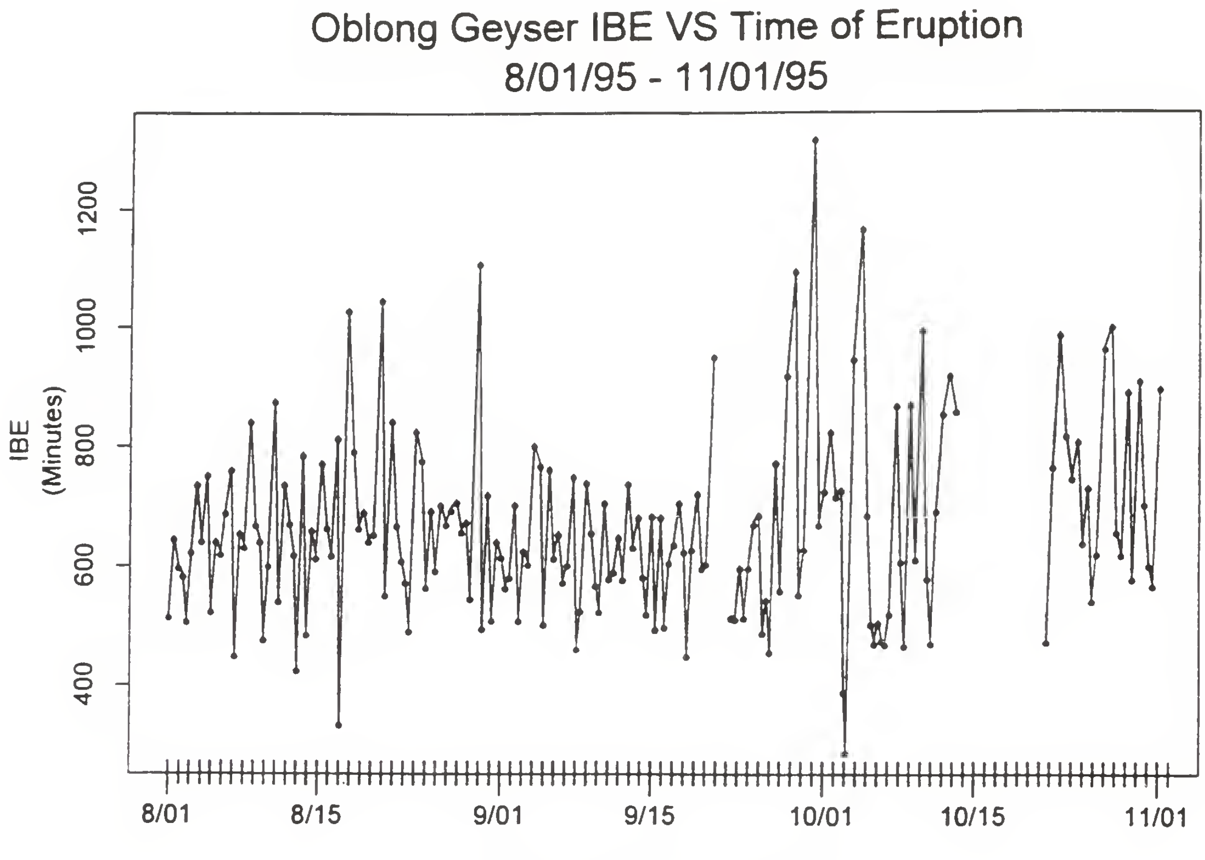


Figure O2

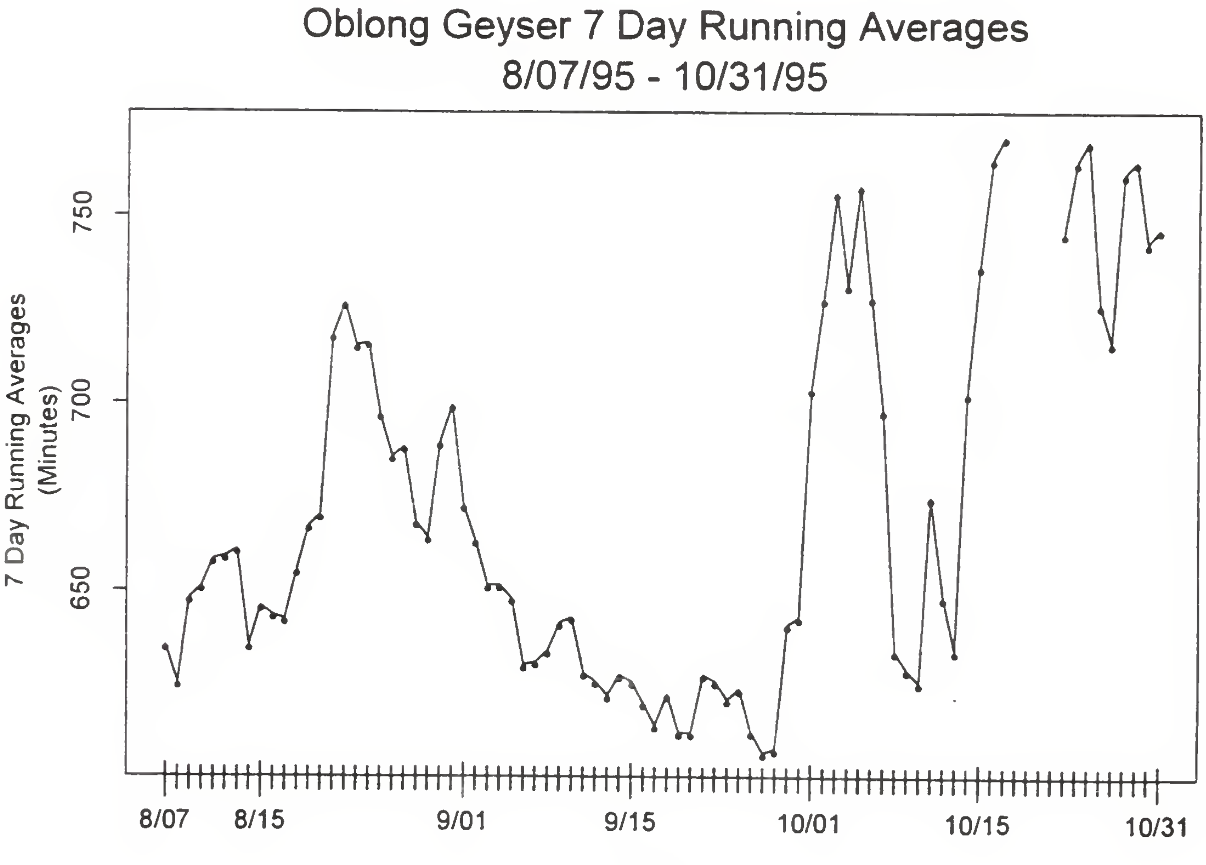


Figure O3

Oblong Geyser 7 Day Running Medians
8/07/95 - 10/31/95

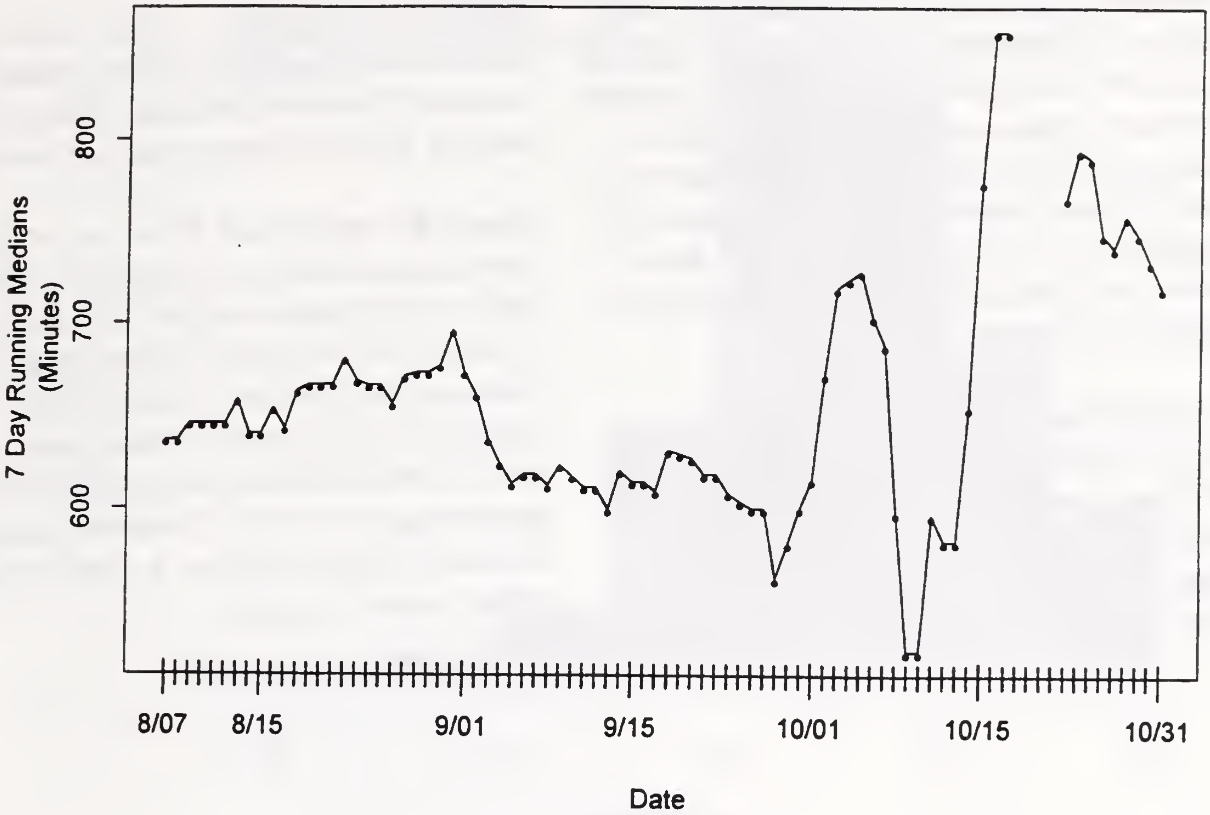


Figure O4

RIVERSIDE GEYSER

Between 6/22/95 and 9/19/95, 287 IBE were obtained. IBE were determined from eruption times extracted from the Old Faithful Logbook and the Carnegie computer. **Figure R1** is a histogram of the distribution of IBE; there is a clear bimodal tendency. The histogram suggests two very different distributions, both of which are symmetric about their own unique measures of center.

To get further insight into the overall distribution of Riverside IBE, the data were split into IBE less than 400 minutes and IBE greater than 400 minutes. The results are given in **Figures R2** and **R3**, respectively. This represents a very crude cut, yet still allows some insight into each mode. A future study will consider the possibility that the overall distribution of Riverside IBE is the result of random samples from two distinct normal distributions.

Figure R4 and Figure R5 are series of seven-day running averages and medians, respectively. Both figures suggest a cyclical nature in Riverside Geyser IBE. More distinct in the series is the shift to an overall decrease in IBE beginning in mid-August. Note, however, that the decline in IBE occurs uniformly beginning approximately 7/29/95. Once the change to decreased IBE is complete, a cyclical pattern begins to emerge again.

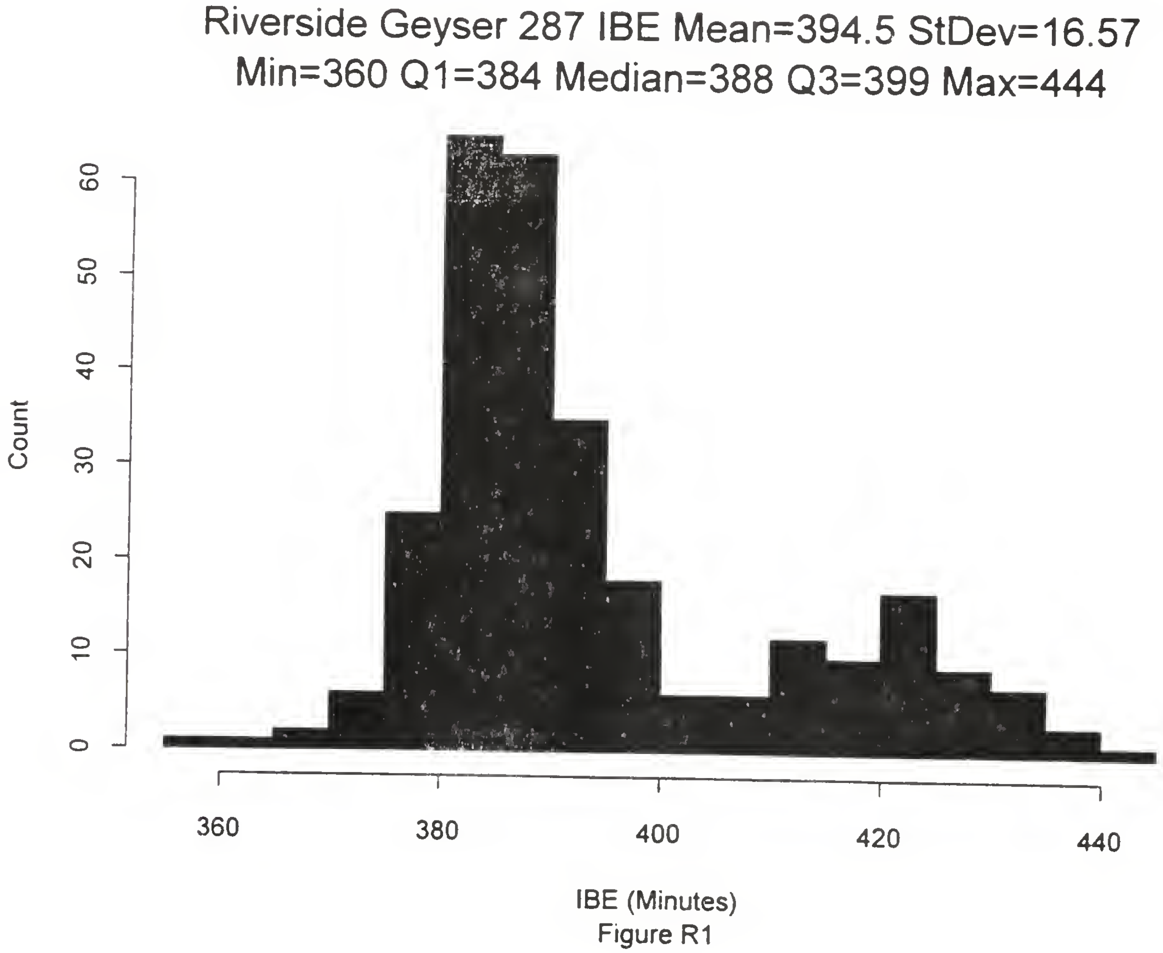
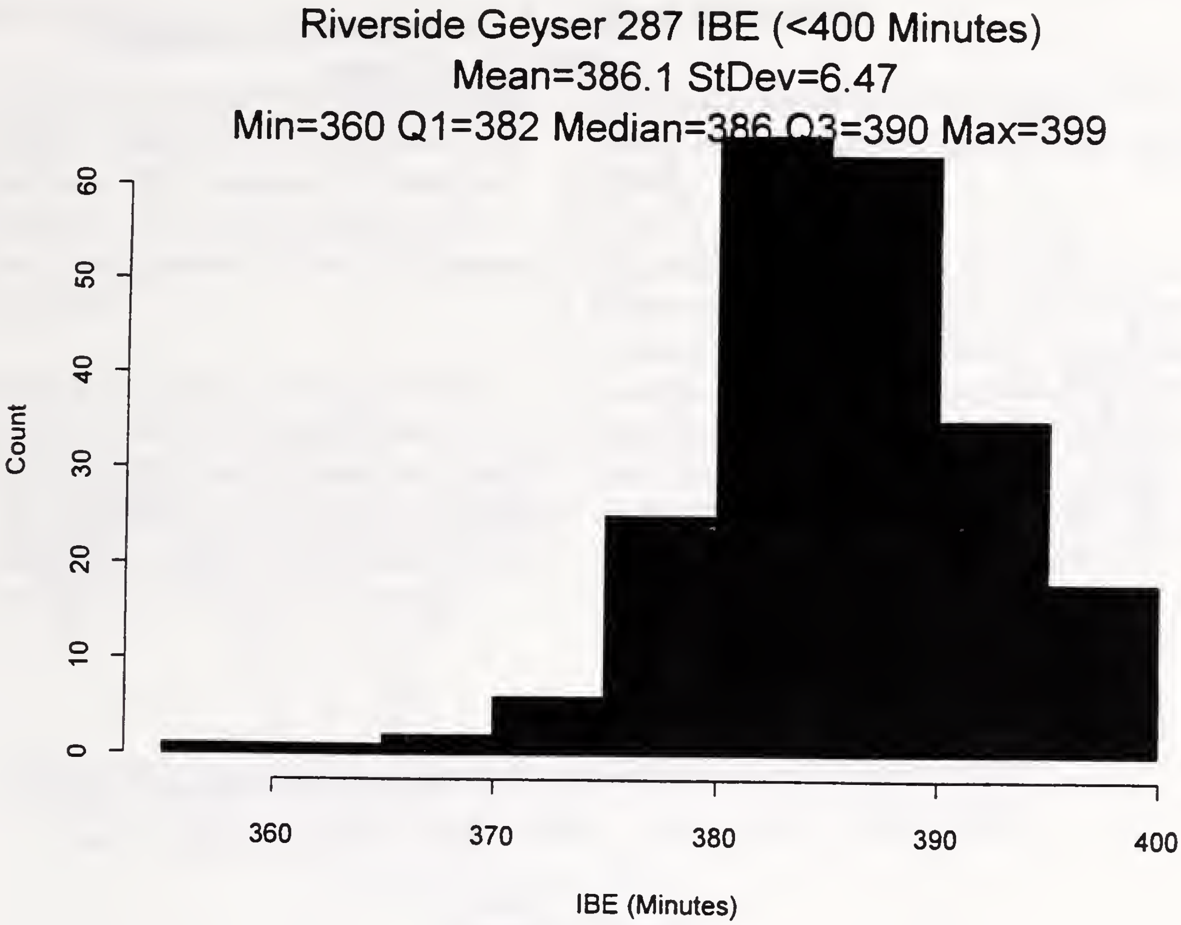
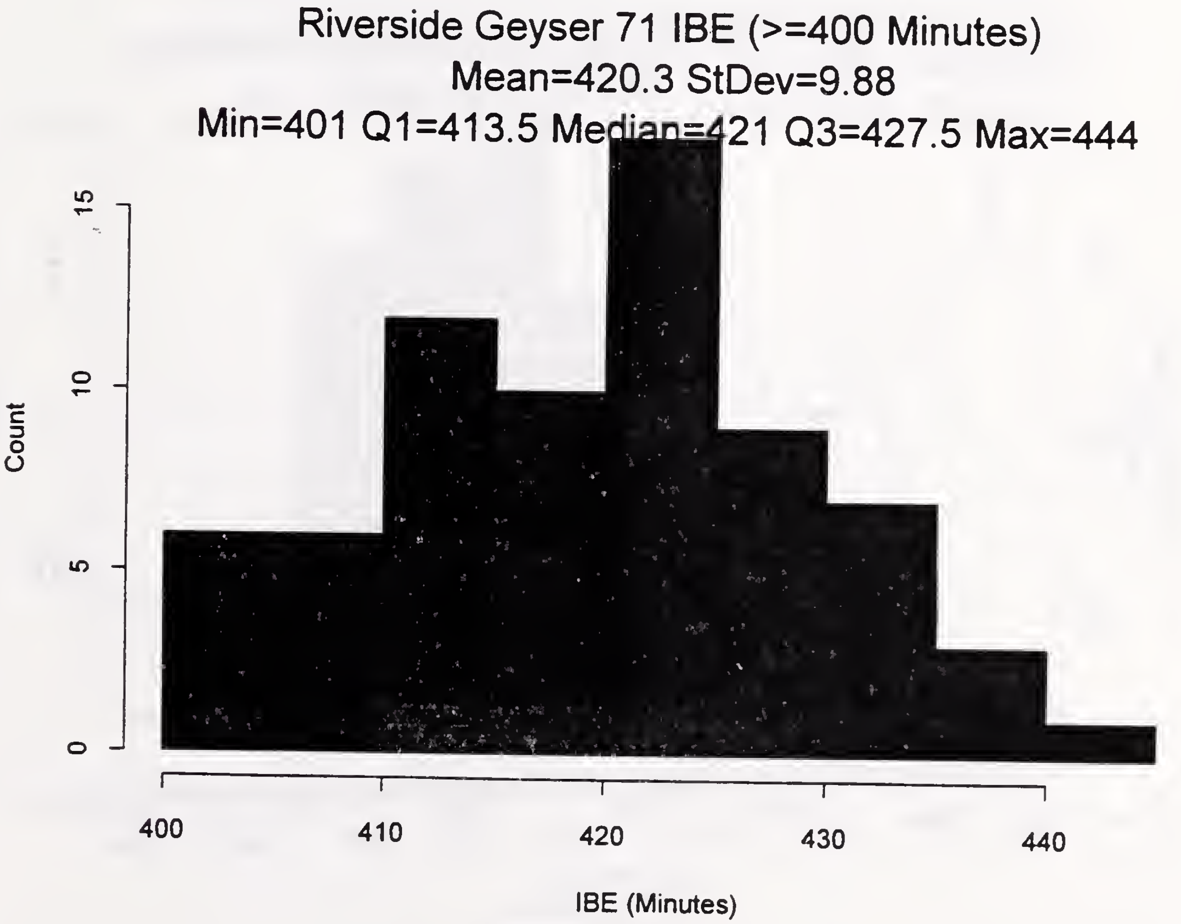


Figure R1



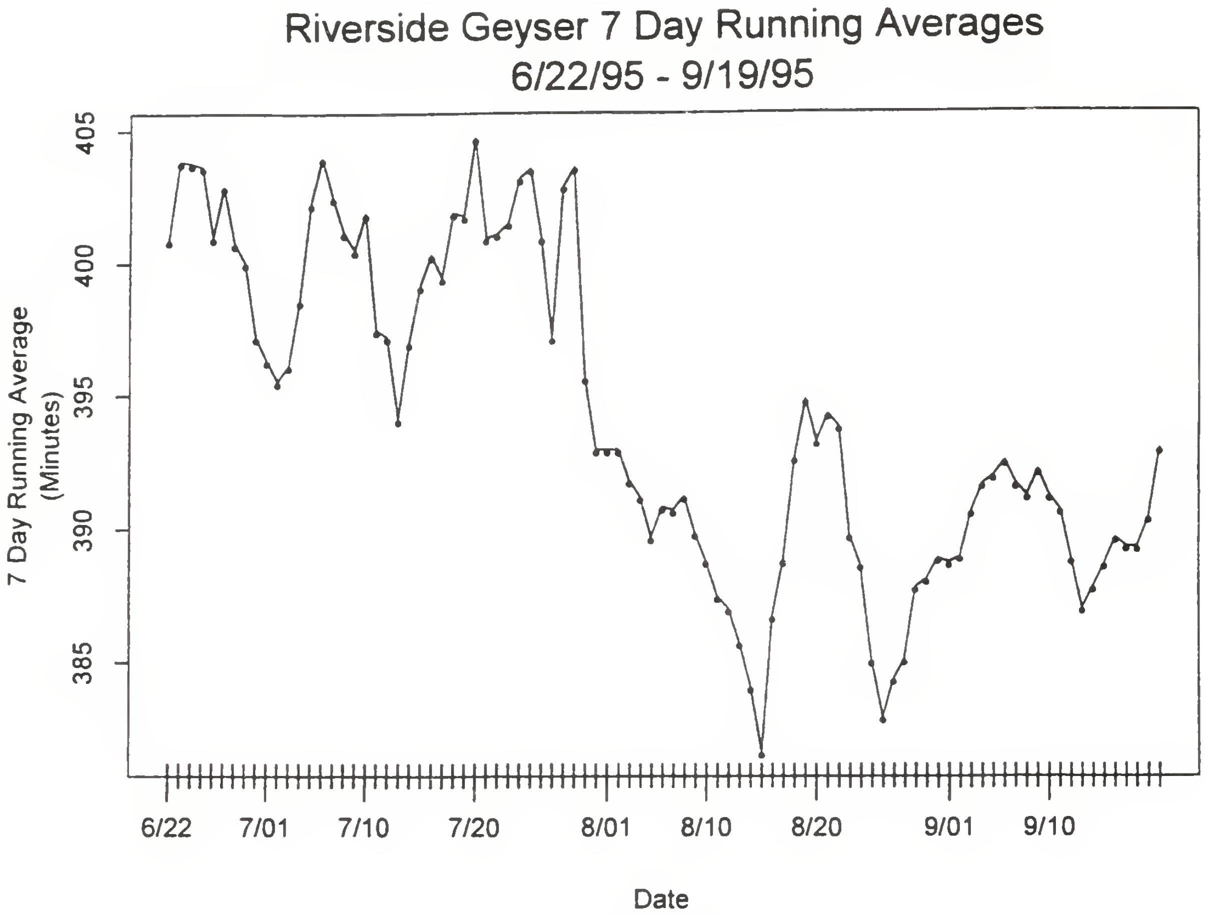
Riverside Geyser 287 IBE (<400 Minutes)
Mean=386.1 StDev=6.47
Min=360 Q1=382 Median=386 Q3=390 Max=399

Figure R2



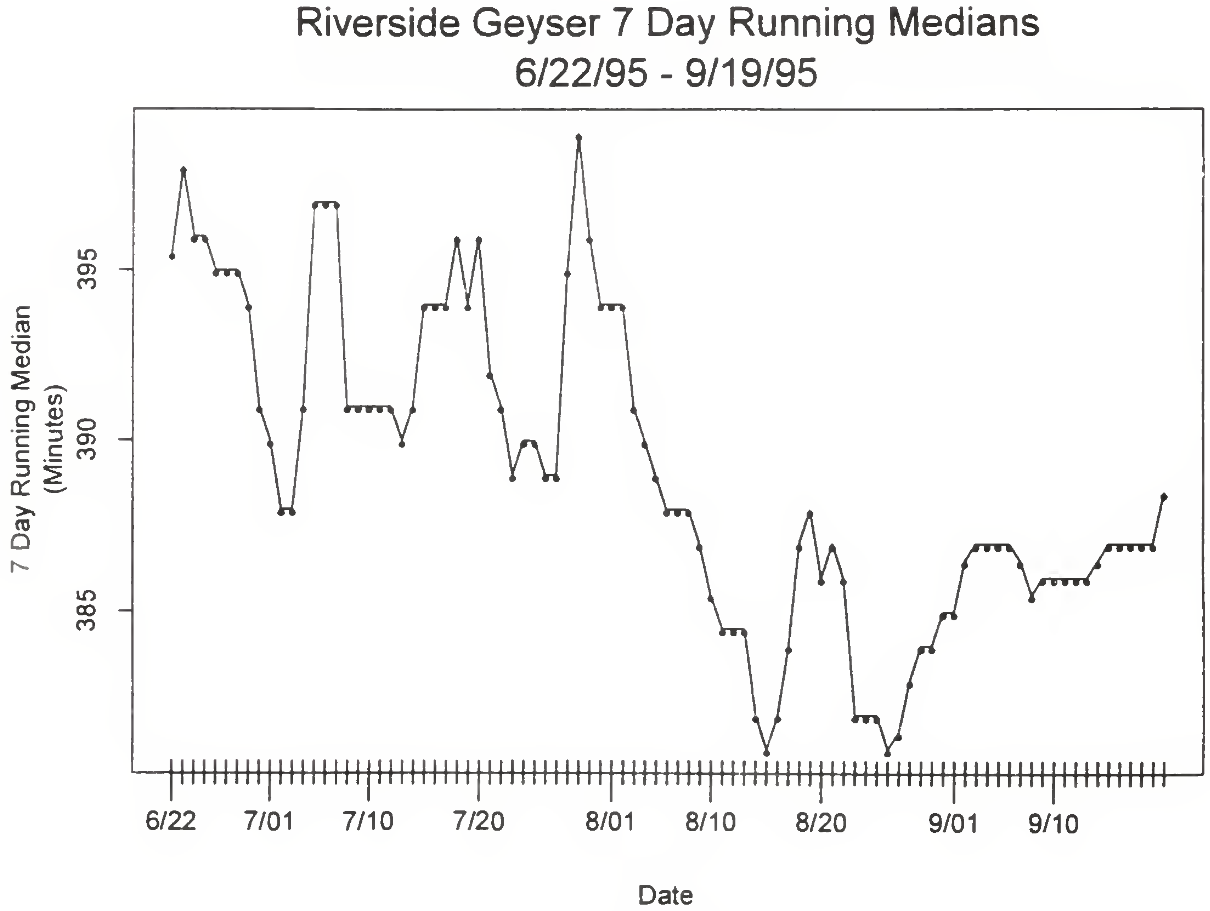
Riverside Geyser 71 IBE (>=400 Minutes)
Mean=420.3 StDev=9.88
Min=401 Q1=413.5 Median=421 Q3=427.5 Max=444

Figure R3



Riverside Geyser 7 Day Running Averages
6/22/95 - 9/19/95

Figure R4



Riverside Geyser 7 Day Running Medians
6/22/95 - 9/19/95

Figure R5

GRAND GEYSER

Between 3/27/95 and 9/09/95, 367 IBE were determined. **Figure G1** is a histogram of the distribution of IBE. Summary statistics are also presented. (See "Grand Geyser 1993-1995" for a comparison of Grand IBE between 1993 and 1995.)

Figure G2 is the series of consecutive IBE plotted versus time of eruption. There is a slight gap in the data record occurring in mid-May. There appears to be a slight trend resulting in an increase in IBE. The maximum IBE of 998 minutes is the longest recorded/observed during the past several years. This trend will be examined further in the current study.

Figures G3 and Figures G4 are series of seven-day running averages and seven-day running medians, respectively. Again, there is a suggestion of slightly increasing IBE. Of interest is the series between mid-August and early September. This coincides with the increasing trend of Plume Geyser during the same time period (Figures P6 and P7).

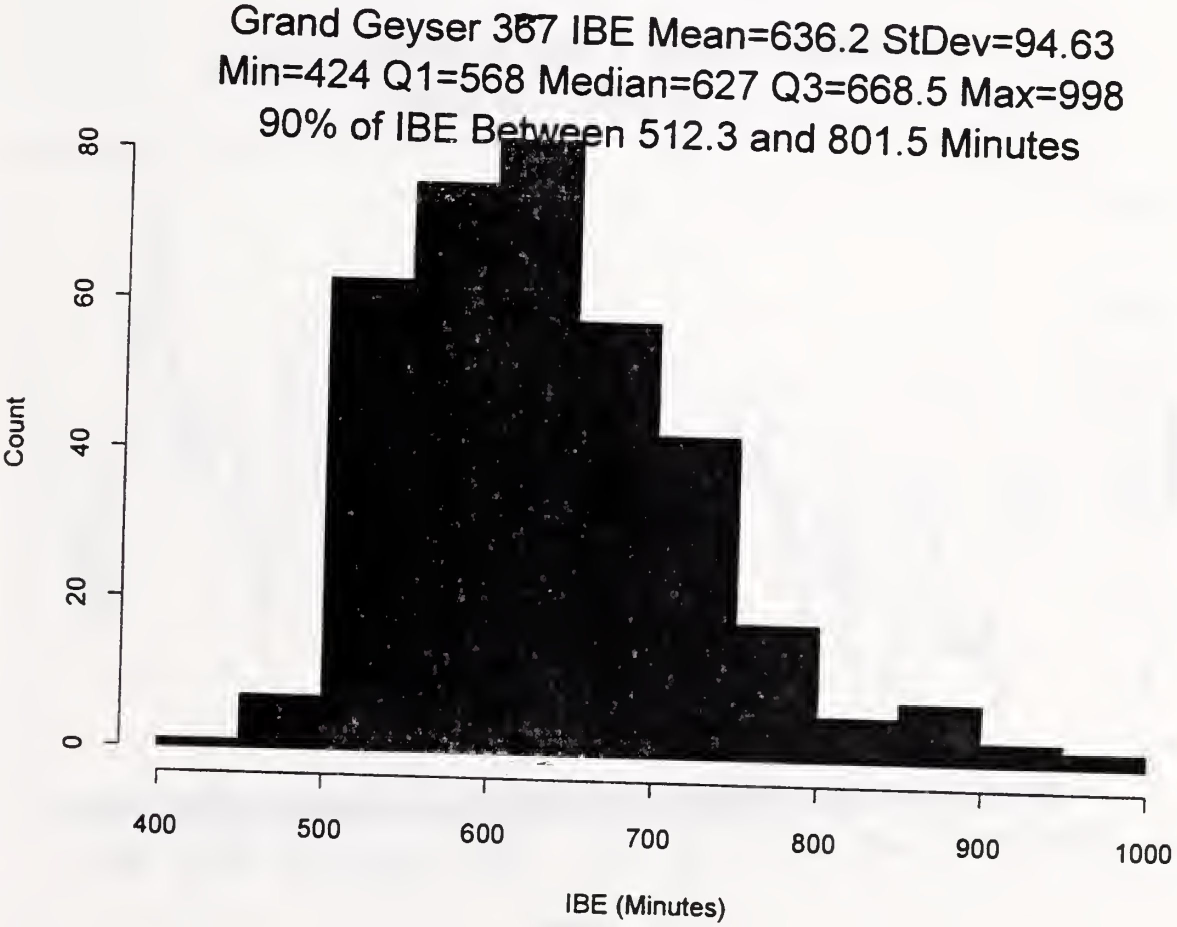


Figure G1

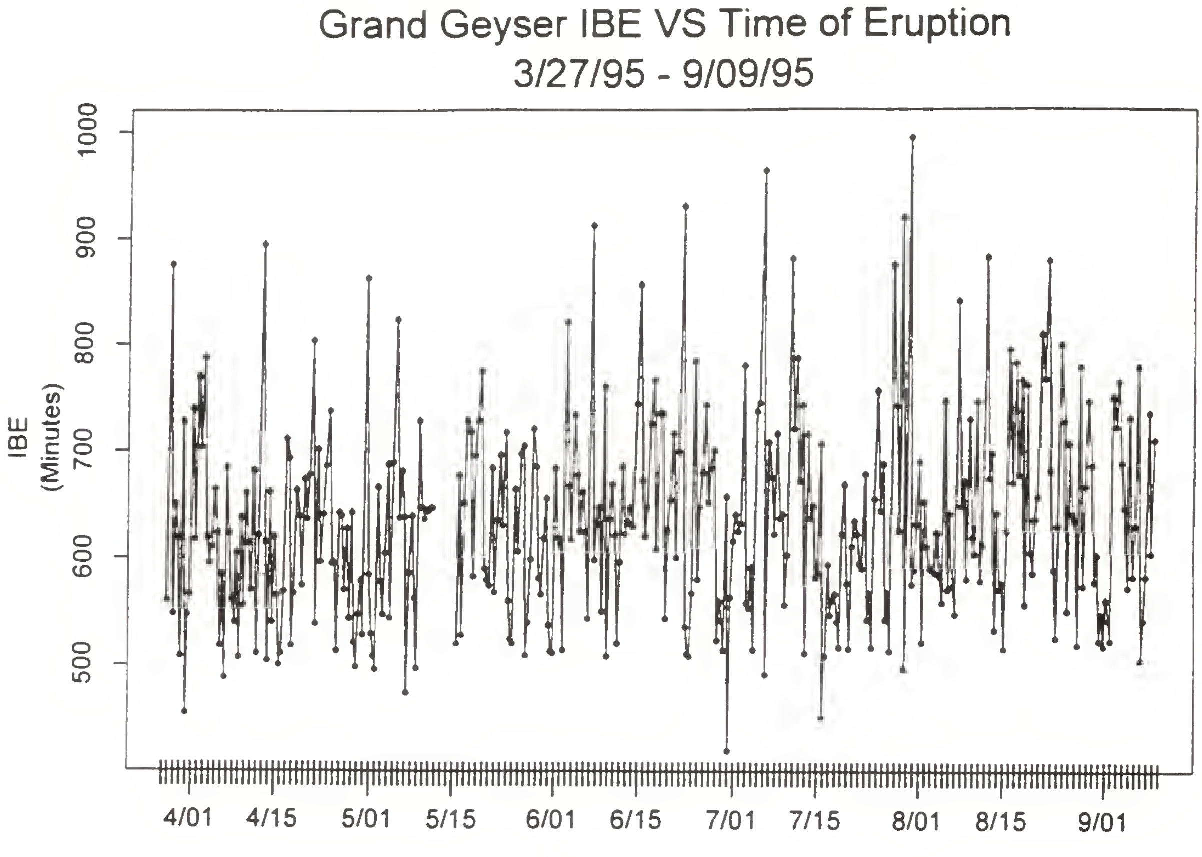


Figure G2

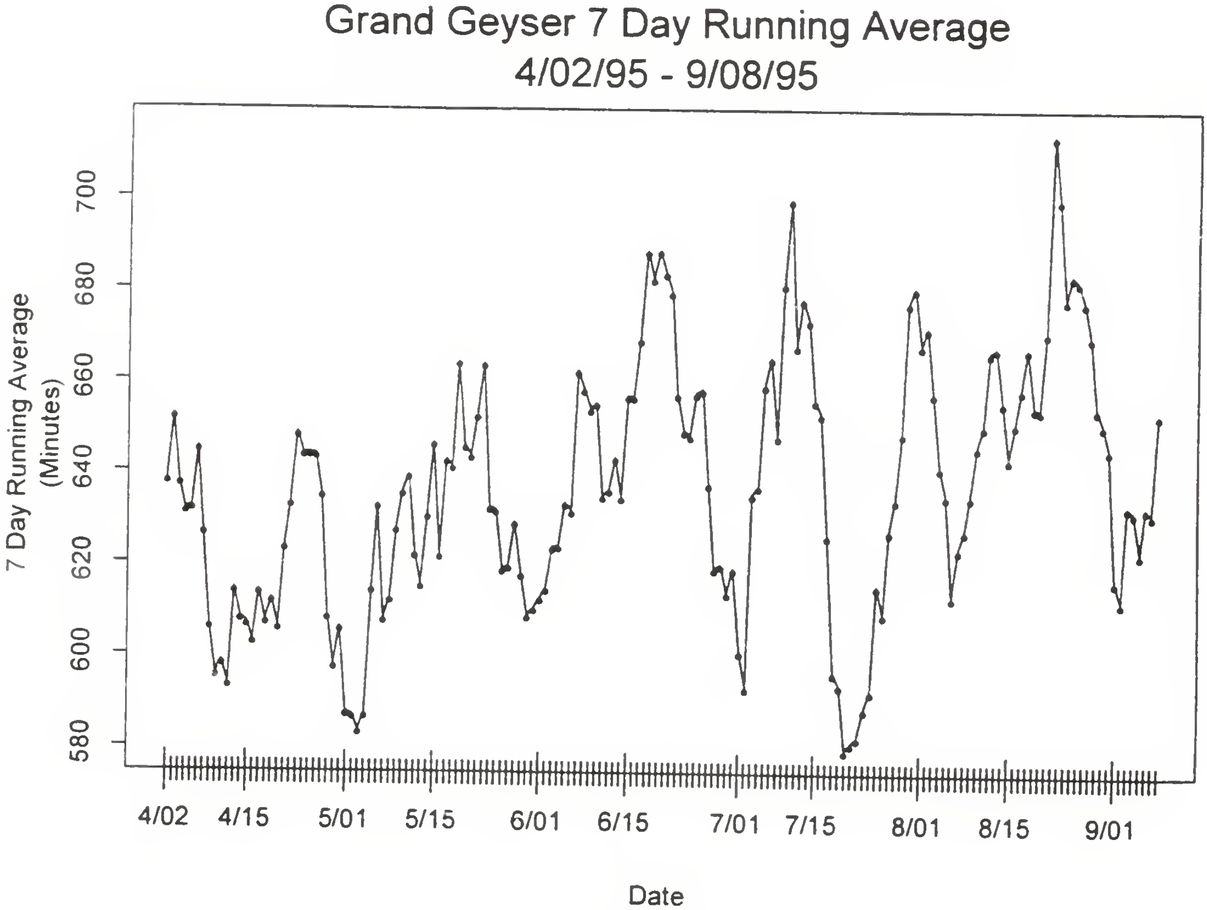
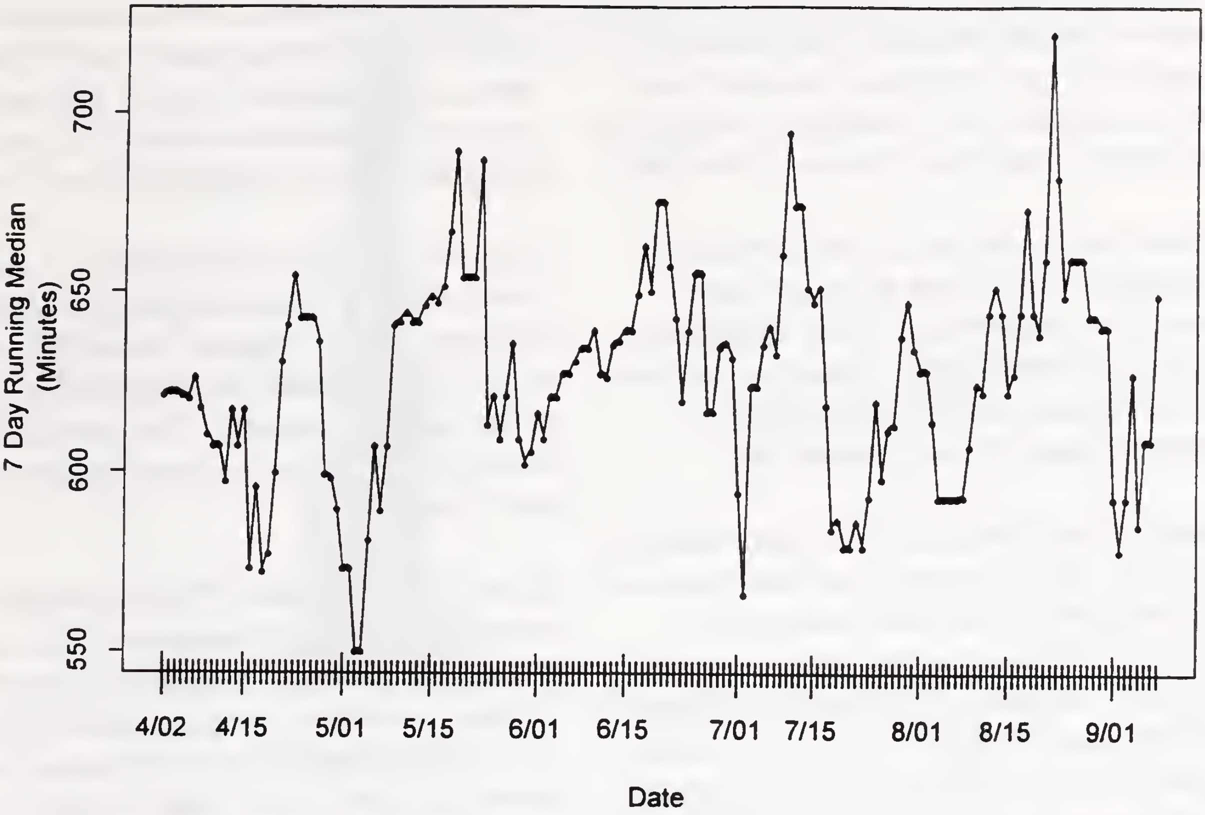


Figure G3



Grand Geyser 7 Day Running Medians
4/02/95 - 9/08/95

Figure G4

DAISY GEYSER

Between 4/23/95 and 11/01/95, 2170 IBE were obtained. In general, Daisy IBE tended to be longer that those obtained in previous years. The comparative study includes an analysis of this change. (See Daisy Geyser: 1994-1995.)

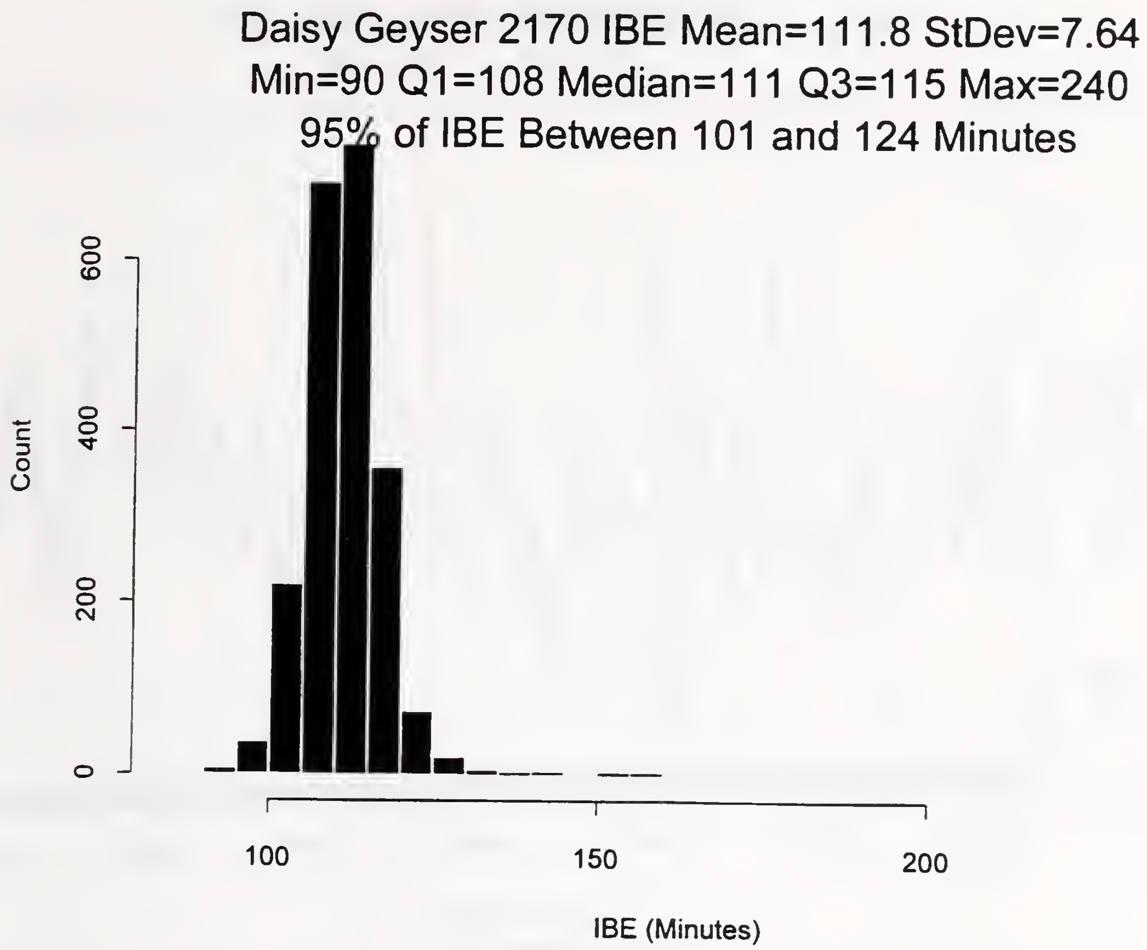
Included in the analysis of the 1994 data (Thompson 1994), there was a discussion referring to a response by Daisy Geyser to an eruption of Giant Geyser. Again, an eruption of Giant Geyser on 9/25/95 resulted in a general increase in Daisy Geyser IBE.

Figure D1 is a histogram of the distribution of 2170 IBE. As in past years, the distribution of IBE is relatively symmetric about center measures. The mean and median are within 0.8 minutes of each other. Note that 95 percent of all IBE were within 101 and 124 minutes, resulting in very stable predictions by the Old Faithful naturalists. The few IBE greater than 140 minutes are most likely the result of one or two Splendid Geyser eruptions and several Splendid Geyser false starts.

Figure D2 and Figure D3 are series of median IBE and mean IBE by day, respectively. Prior to 9/25/95, Daisy IBE fluctuates about a relatively stable center point. On 9/25/95, there is a considerable jump in IBE which persists for at least nine days. This jump coincides with the eruption of Giant Geyser.

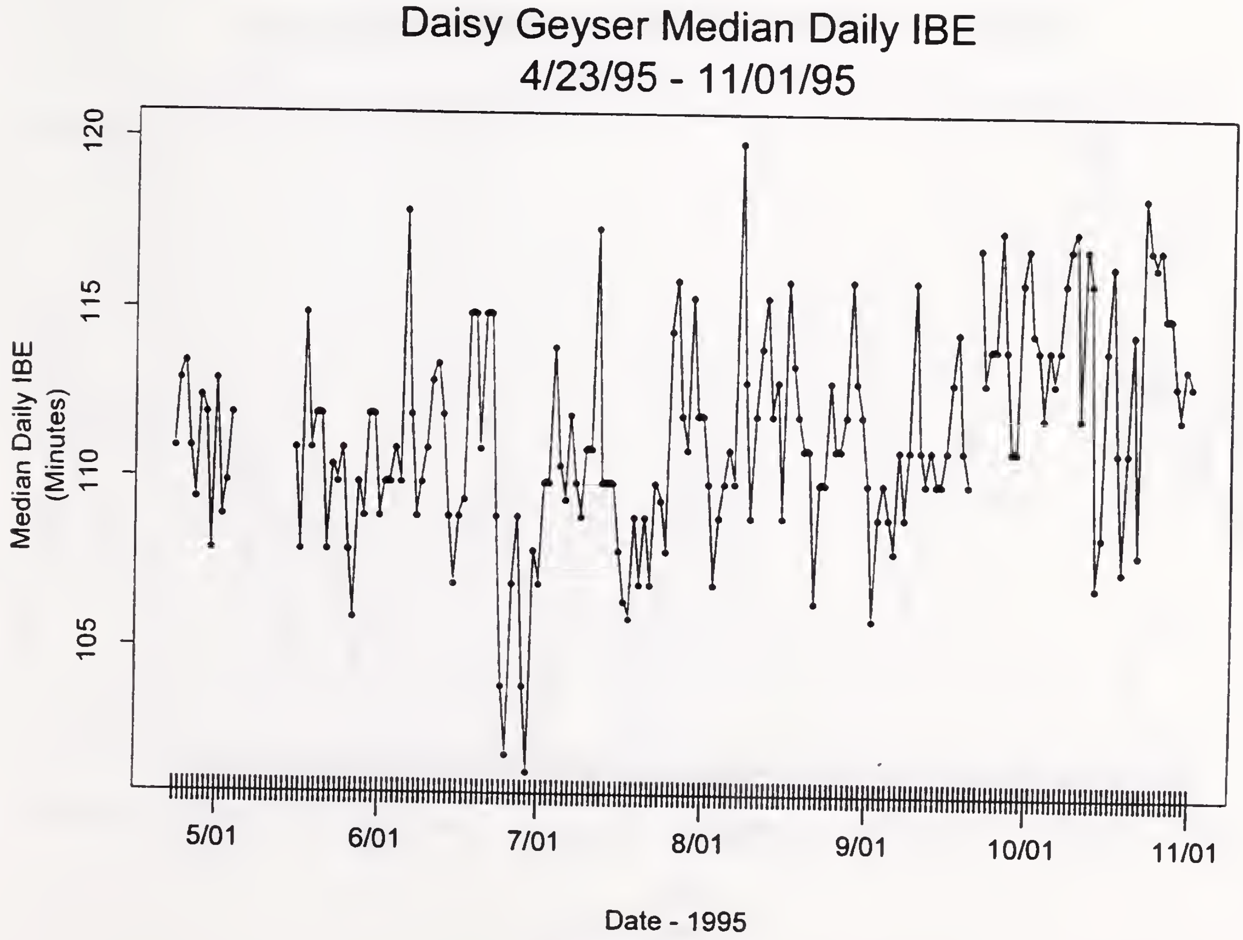
As in the past, Daisy IBE tends to be reduced during daylight hours and increased during nighttime hours. **Figures D4 and D5** are, respectively, median and mean IBE by hour in which eruption occurred. The decreased IBE during daylight hours is clearly exhibited in both figures.

Figure D6 and Figure D7 are seven-day running averages and medians of IBE, respectively. The response to Giant Geyser is clearly evident. In addition to an increase in IBE due to the Giant eruption, there is evidence suggesting a slightly less dramatic overall increase in IBE beginning in late July. The hypothesis offered for this earlier increase in IBE is that this is a response to the activation of Oblong Geyser. The comparative study includes an analysis of the 1994 data.



Daisy Geyser 2170 IBE Mean=111.8 StDev=7.64
Min=90 Q1=108 Median=111 Q3=115 Max=240
95% of IBE Between 101 and 124 Minutes

Figure D1



Daisy Geyser Median Daily IBE
4/23/95 - 11/01/95

Figure D2

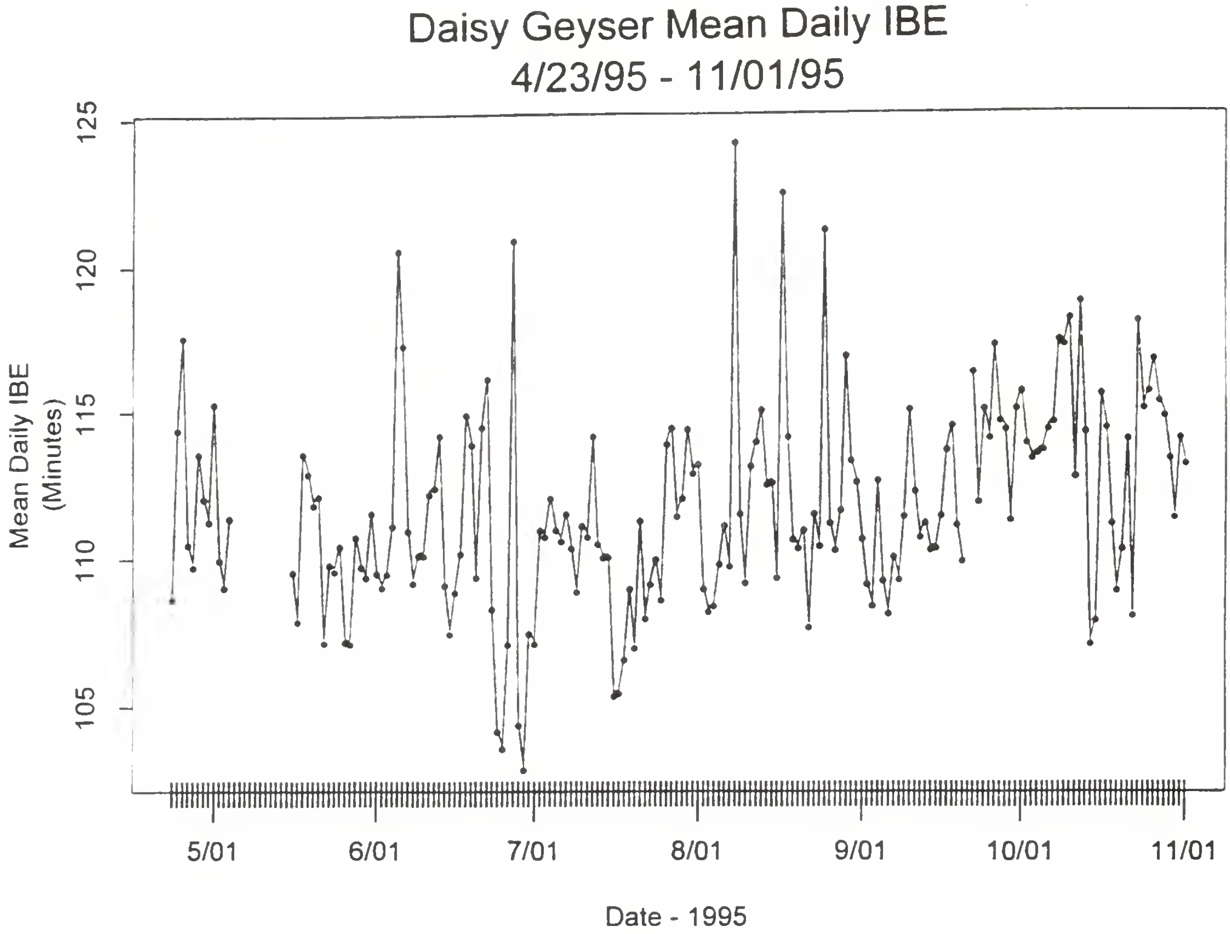


Figure D3

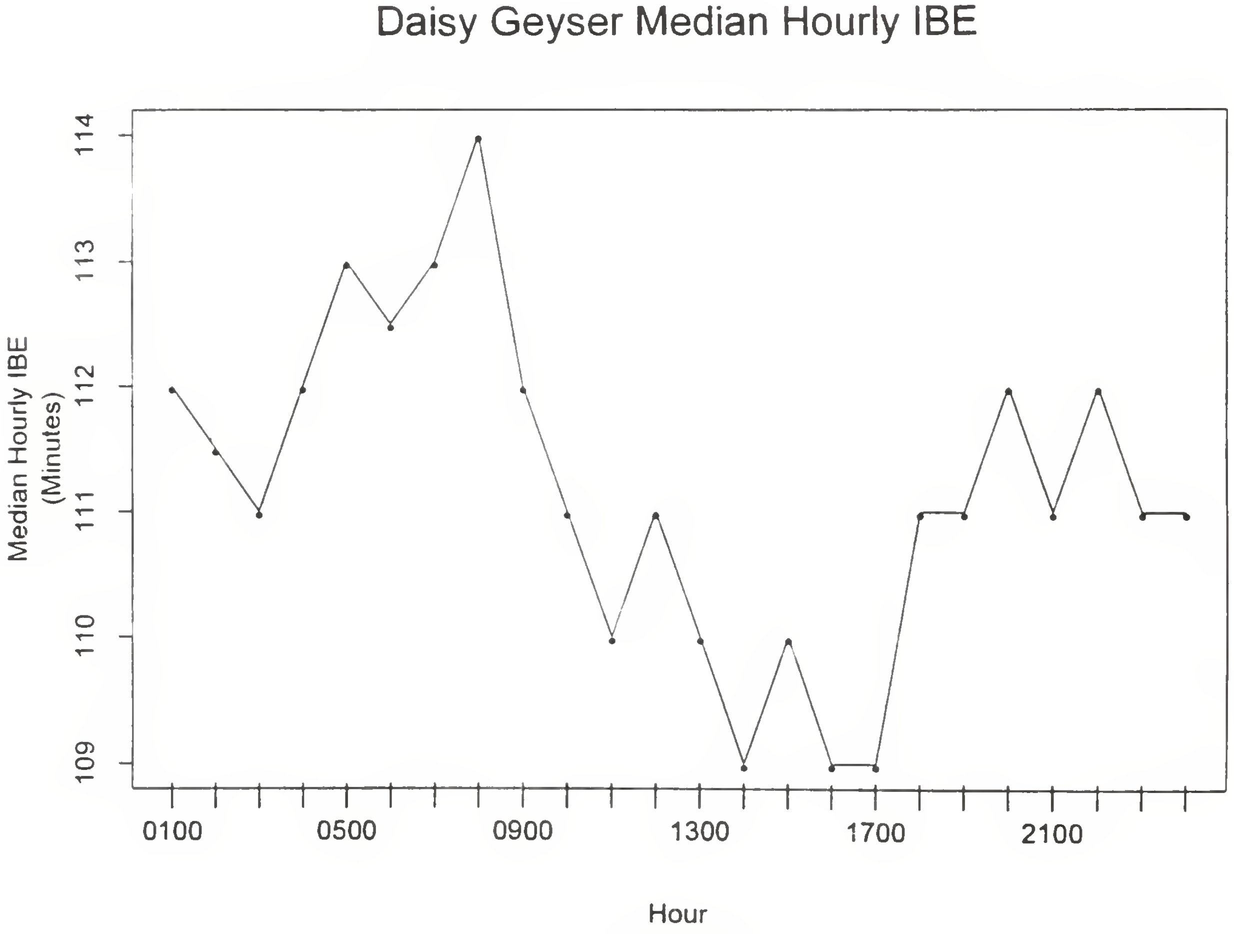


Figure D4

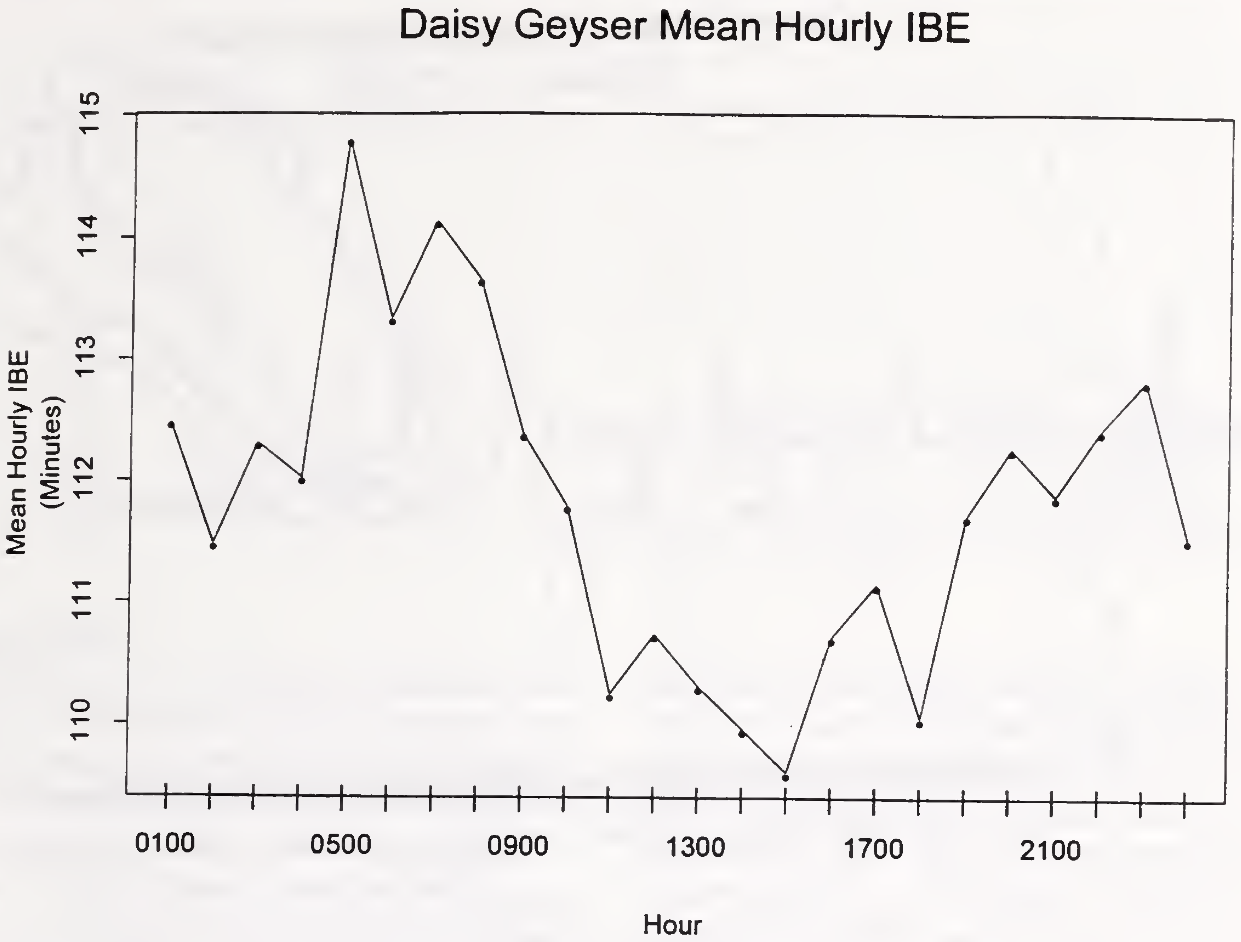


Figure D5

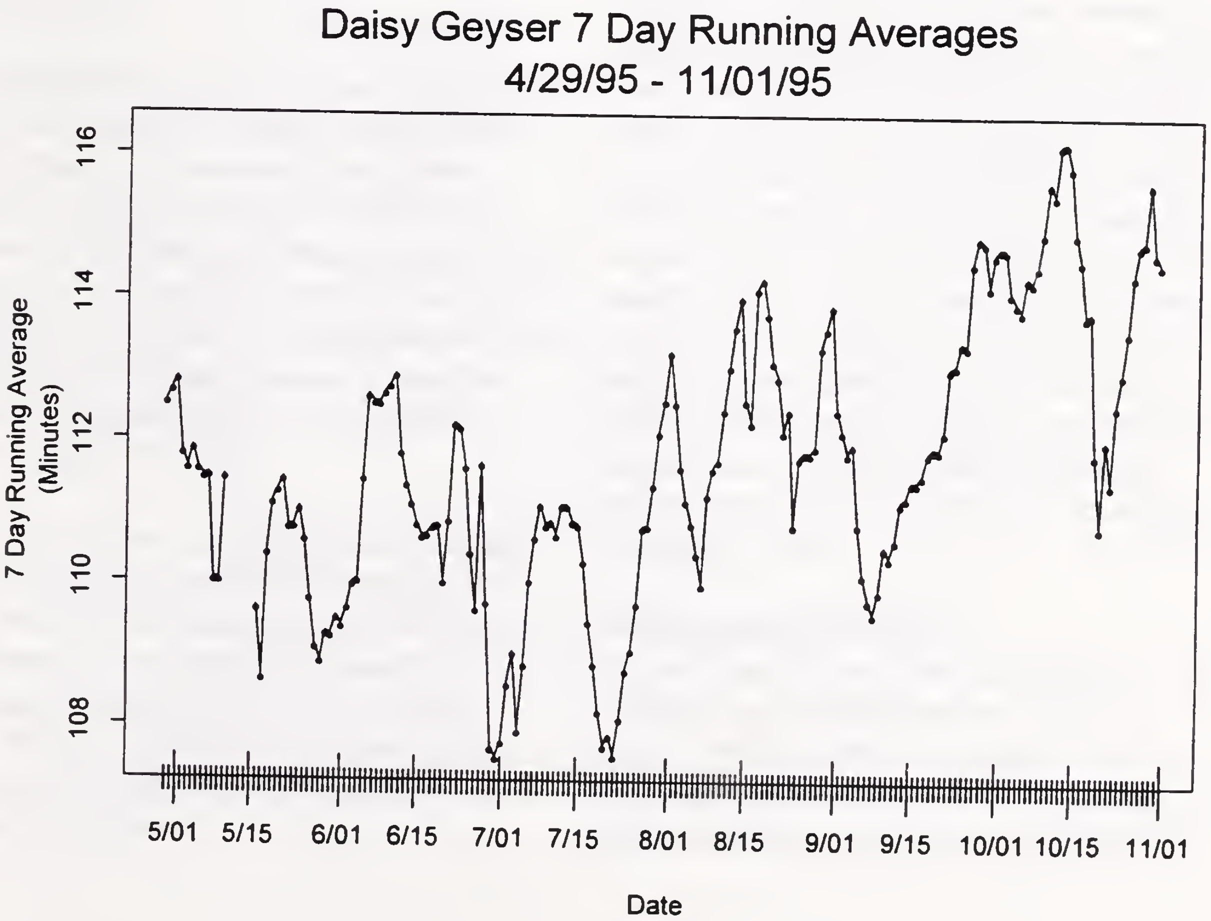


Figure D6

Daisy Geyser 7 Day Running Medians
4/29/95 - 11/01/95

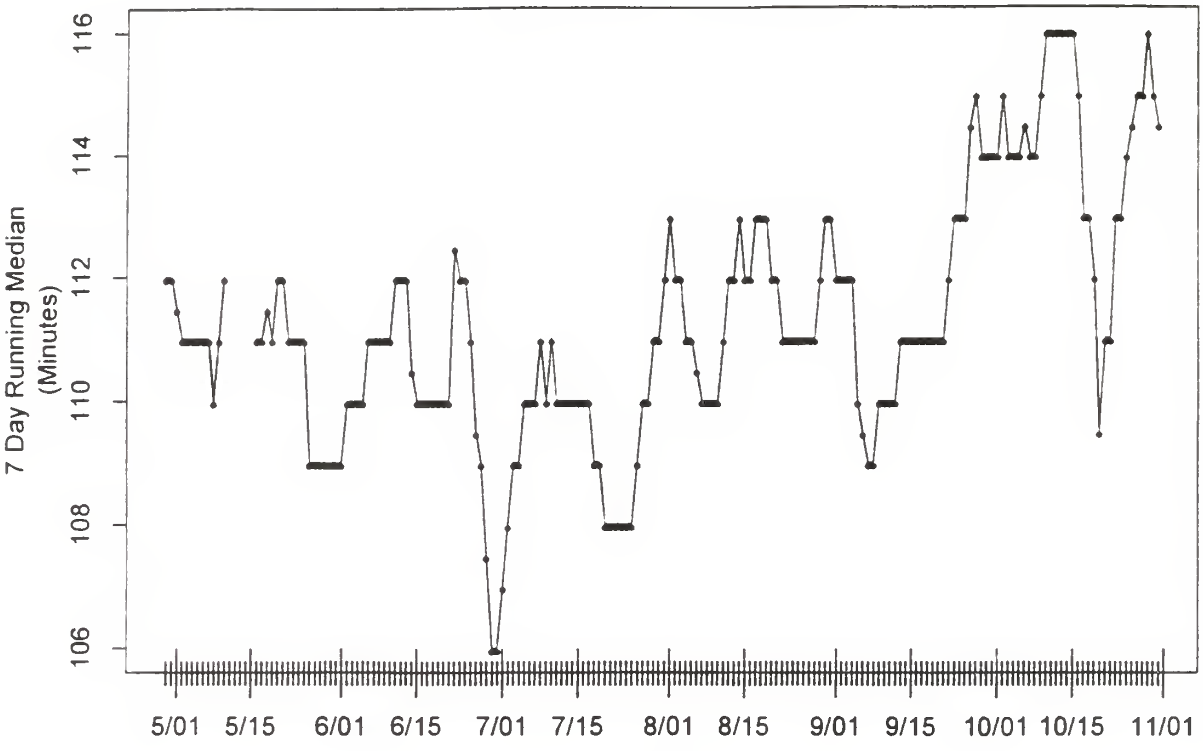


Figure D7

DAISY GEYSER : 1994–1995

Introduction

Beginning in 1994, we began electronic monitoring of Daisy Geyser to obtain eruption times and construct long-term series of intervals of times between eruptions (IBE). Such monitoring continued in 1995 and into the present year. A major change in eruption activity occurred in the fall of 1994 resulting in a shift to increased IBE. A second shift occurred in the fall of 1995.

This report focuses on two causes of the shifts in eruption activity and compares both series of IBE. First, it appears that Daisy Geyser responds to eruptions of Giant Geyser. Second, there is increasing evidence to support the hypothesis that changes in observed activity of the Upper Geyser Basin occurred basin-wide in the fall of 1994. This represents a possible response to a major change in geothermal forces acting on the basin.

This report is based on the results of eruption times of Daisy Geyser obtained through electronic and/or visual observations. Intervals of times between the onsets of consecutive eruptions are determined from the eruption times. For the remainder of this report, the intervals are referred to as IBE. All IBE are recorded in minutes.

Between 1990 and 1993, eruptions of Daisy Geyser were very predictable. It is well documented that prior to the fall of 1994 (Old Faithful Logbooks 1990–1994), eruptions of Daisy Geyser were very consistent, with IBE in the range of 90 to 110 minutes. With IBE generally below 120 minutes, visitors to the Upper Geyser Basin can almost always view an eruption of Daisy without compromising a great deal of their time. However, on occasion Daisy does tend to have IBE in excess of two hours. In past years, these longer IBE were most often the result of eruptions of nearby Splendid Geyser. An eruption of Splendid Geyser usually leads to an increased IBE of the Daisy Geyser eruption immediately following. Upon its next eruption, Daisy Geyser reverts back to its pre-Splendid eruption activity. As will be pointed out in this report, regardless of eruptions of Splendid or Giant Geysers, a major increase in IBE of Daisy Geyser began in the fall of 1994.

Distributions and Series

Figure 1 and **Figure 2** are histograms of the distributions of IBE for the data collected during 1994 and 1995, respectively. To account for Splendid Geyser's influence on Daisy, resulting in longer Daisy IBE, IBE greater than 130 minutes were removed from the data frame prior to the construction of the histograms. Both distributions are symmetric about their respective centers of measure. Given the high predictability of eruption times, such symmetry is not surprising.

The figures strongly suggest that a shift toward increasing IBE occurred between 1994 and 1995. However, the reader should bear in mind that Figure 2 represents an additional three months of data as compared to the distribution represented in Figure 1. A brief summary of both years is given in **Table 1** (times are in minutes).

Prediction windows reflecting a 95 percent probability for the minimum and maximum intervals (based on the lower 2.5 and the upper 97.5 percentiles) are as follows:

Year	95% Prediction Window Minimum	Maximum
1994	94	118
1995	101	124

The approximate equality of the mean and median within each distribution are representative of the symmetry displayed in the figures. The relatively high standard deviations result from longer IBE due to the rare interaction with eruptions of Splendid. It is of note that all statistics (with the exception of standard deviation) shifted an overall increase of 7 minutes.

To account for the longer time frame of data collected in 1995, distributions were reconstructed for similar time periods of each year. **Figure 3** and **Figure 4** are histograms of Daisy IBE from the end of July to the first of November each year (IBE resulting from interactions with Splendid have again been removed). Removing the data from late April through late July of 1995 does not affect the shift toward increasing IBE, indicating the shift is not an artifact of the additional three months of the data collected in the spring of 1995. The summary of the adjusted time-frame is given in **Table 2**.

Prediction windows for the minimum and maximum intervals (using only the data from comparable time periods in 1994 and 1995 are:

Year	95% Prediction Window Minimum	Maximum
1994	94	115
1995	104	125

Table 1. Comparison of statistics for Daisy Geyser intervals, 1994—1995.

Year	Minimum	Q1	Median	Mean	Q3	Maximum	St.Dev.
1994[a]	87	101	104	104.8	108	395	9.93
1995[b]	90	108	111	111.8	115	240	7.64

[a] n = 1487 IBE
[b] n = 2170 IBE

Table 2. Comparison of Daisy Geyser intervals adjusted to equalize time period covered, 1994—1995.

Year	Minimum	Q1	Median	Mean	Q3	Maximum	St.Dev.
1994[a]	87	100	104	104.1	107	395	9.90
1995[b]	98	109	112	112.9	116	201	6.67

[a] n = 1346 IBE
[b] n = 1143 IBE

The resulting overall increase in IBE based on the truncated time-frame is approximately 8 minutes, evidence that the shift to increased IBE occurred between 11/01/94 and 7/26/95. The next section of this report concentrates on a more detailed search for the change which occurred in the eruption cycles of Daisy Geyser.

Major Change and Evidence Supporting an Event acting on the Upper Geyser Basin

For both the 1994 and 1995 series, IBE were first plotted versus time of eruption. Increasing and decreasing IBE occurred throughout these series. The most dramatic increase begins on 10/20/94. Within seven days, Daisy Geyser IBE increased from a range of 103–105 minutes to 110–114 minutes. Upon this discovery, seven-day running averages and seven-day median traces were constructed from each of the data frames. All major trends in IBE show up clearly.

These seven-day moving averages tend to result in a loss of some resolution, but trends are easily viewed using graphical techniques. **Figures 5, 6 , 7,** and **Figure 8** are the resulting graphs of the smoothed IBE series. Figures 5 and 7 show a substantial increase in IBE beginning approximately 10/20/94 and continuing throughout the time period of data collection ending 11/11/94. When data collection began again on 4/29/95, the trend of higher IBE continued but had stabilized (see Figures 6 and 8.)

It seems reasonable to assume that the increase of IBE stabilized sometime between 11/11/94 and 4/29/95. The running averages and median traces of Figures 6 and 8 suggest that IBE never returned to a long-term trend for shorter intervals. For the first time in the history of research of Daisy Geyser's activity, we have documented a major shift in eruption behavior of Daisy Geyser through the use of continuous data collection techniques. At the time of this report it is unclear whether local or near seismic events occurred during the time frame of the noted increase.

Whatever the cause of change, Daisy Geyser is not the only thermal feature exhibiting dramatic change during the fall of 1994. In another chapter we document that Grand Geyser underwent a major change during the same time period (see "Grand Geyser 1993–1995"). IBE of Grand Geyser increased significantly beginning mid-fall of 1994. Also, Castle Geyser began to show an increase in minor type of eruptions in 1994 and by the spring of 1995, predictions of Castle Geyser eruptions could seldom be accurately obtained. This represents a dramatic change when compared to 1993, in which very few minor eruptions were recorded.

Secondary Shifts: Oblong Geyser and Giant Geyser Influences

Oblong Geyser is located up-river from the Giant Geyser complex of the Upper Geyser Basin. It would seem doubtful that eruption activity of Oblong Geyser could influence activity of the Daisy Geyser complex. Further examination of Figures 5-8 suggest otherwise. Oblong Geyser reactivated in late-July or early August of 1994. A close inspection of Figure 5 and Figure 7 indicate an increase in Daisy IBE beginning in the same time frame. Oblong was then dormant following an eruption of Giant Geyser on 9/29/94. Oblong next reactivated in mid-July of 1995. Figure 6 and Figure 8 once again indicate an increase in Daisy IBE. The evidence supports a subtle influence of Daisy upon activation of Oblong Geyser.

There is historical documentation suggesting an interfunctional relationship between the

Daisy Geyser complex and Giant Geyser complex (Marler 1973). There is clear evidence in this study strongly supporting George Marler's hypothesis. As mentioned earlier, Giant Geyser erupted on 9/29/94. Giant also erupted on 9/25/95. The seven-day running averages (Figures 5 and 6) indicate a short-term trend of increased Daisy IBE. The short-term trend is not apparent in the seven-day running medians of the 1994 data (Figure 7), but is supported by the seven-day running medians of the 1995 data. The discrepancy between the means and medians of the 1994 data can be explained and does not cause us to reject a hypothesis of an interfunctional relationship between the Giant complex and the Daisy complex. The maximum Daisy IBE of 395 minutes in 1994 occurred within a few hours of the 1994 Giant eruption. This interval also explains the inflated seven-day running means observed in the 1994 series. It is the assumption that the 395 minutes IBE resulted from a series of Splendid Geyser eruptions or, at the very least, a series of powerful false-starts of Splendid Geyser eruptions. Given Marler's comments and the trend of temporarily increased IBE during the eruption of Giant in 1995, it is beyond coincidence that the Daisy complex reacted during the eruption of Giant Geyser in 1994.

Marler strongly suspected that Oblong Geyser is also closely related to the Giant Geyser complex. This author concurs with Marler's observation. Activities of Oblong Geyser, the Giant Geyser complex, and the Daisy Geyser complex are all related. It is a reasonable conjecture that there exist two separate but connected fractures in the rhyolite foundation supporting these geyser groups. Further possible evidence of such a connection might be enhanced through chemical analysis of chloride concentrations.

Seismic Influences

From mid-June through mid-July of 1995, local earthquake swarms involving thousands of seismic events occurred within the Yellowstone region. Figures 6 and 8 indicate rapid decreases in IBE during approximately the same time period. In fact, a review of the entire data frame of 1995 results in the conclusion that this was the only time period in which we recorded consistently lower IBE compared to neighboring time periods. The rapid drop in IBE beginning approximately 6/27/96 is perhaps a precursory signal of an intense earthquake swarm resulting in 500 earthquakes recorded on a single day at the beginning of July.

Conclusion

Currently, there is no definitive explanation for the increasing IBE of Daisy Geyser during the fall of 1994. The evidence for this change does support the hypothesis that the entire Upper Geyser Basin reacted to a major geological event. Whether this event can be precisely determined and described geologically is currently unknown. It is also unknown whether or not such an event would have to occur within the boundaries of the Yellowstone caldera. The task of isolating a change in structural geology inducing thermal changes could be formidable.

This report supports a high degree of interaction between Oblong Geyser, the Giant Geyser complex, and The Daisy Geyser complex. The past season's eruptions of Oblong Geyser led to a subtle increase in Daisy IBE. Eruptions of Giant Geyser also led to a short-term increase in Daisy IBE.

Daisy Geyser appears to have responded to major earthquake swarms during 1995. Continued monitoring of Daisy Geyser might show that rapid changes in Daisy IBE are precursors to major seismic events.

Continued long-term monitoring of Daisy Geyser should lead to increased understanding of the eruption activity of Daisy Geyser, along with a greater awareness of geyser interactions and responses to other local geothermal phenomena.

Literature Cited

Marler, G. 1973. Inventory of Thermal Features of the Firehole River Geyser Basins and Other Selected Areas of Yellowstone National Park. *U.S. Geol. Surv. Report* GD-73-018.

GRAND GEYSER: 1993–1995

Introduction

Beginning in 1993, electronic recording instruments were deployed to record the temperature in the runoff channel of Grand Geyser. Eruptions of Grand Geyser are determined by an extreme change in temperature. Such monitoring continued in 1994, 1995 and into 1996. The harsh winter climate does not allow monitoring during many of the winter months, and gaps in the three-year series of data reflect this. This report focuses on a major shift in eruption activity occurring in the fall of 1994.

Although Grand Geyser has experienced many shifts in behavior over the past 100 years, the behavior of the shifts themselves has not been documented until now. The importance of long term monitoring yields important information for the scientific community and the public. To the scientific community, changes in geyser activity reflect changes in geological forces. To the public, long term monitoring leads to better prediction methods allowing visitors more choices and improved management of their time spent in the thermal regions of Yellowstone National Park.

This report is based on the results of eruption times of Grand Geyser obtained through electronic and/or visual observations. Intervals of times between the onsets of consecutive eruptions are determined from the eruption times. For the remainder of this report, the intervals are referred to as IBE.

A study based on the series of IBE obtained in 1993 served as the basis for a graduate project at the University of Montana. The hypothesis of this study was that for analytical purposes Grand Geyser IBE are centered about a measure of central tendency (mean or median) with departures from center occurring randomly. A Fourier analysis of the series showed no cyclical behavior in the IBE series of 1993. An autocorrelation function showed no significant serial correlation within the series. The implication of such findings suggested that previous eruptions have little influence on following eruptions. With the exception of a shift in eruption activity occurring in the fall of 1994, long series of IBE during all three years appear as independently identically-distributed events.

Distributions and Series

Figures 1, 2, and **3** are histograms of the distributions of IBE series obtained from 1993 through 1995. All three distributions show a strong departure from normality; specifically, all three display a right-skewedness. A brief summary of the three years is given in **Table 1**. Times are in minutes.

Table 1. Comparison of statistics for Grand Geyser intervals, 1993–1995.

Year	Minimum	Q1	Median	Mean	Q3	Maximum
1993	357	460	498	506.8	546	763
1994	379	477	522	536.3	577	919
1995	424	568	627	636.2	689	998

Prediction windows reflecting a 90 percent probability for the minimum and maximum intervals (based on the lower 5th and the upper 95th percentiles) are as follows:

	90% Prediction Window	
Year	Minimum	Maximum
1993	414	622
1994	425	700
1995	512	802

In general, there is an overall increasing trend in IBE. Based on this summary alone, it is tempting to suggest that there is a gradual increase occurring throughout the three years. Plots of the individual series (**Figures 4, 5,** and **6**) for each year suggest otherwise. Figure 4 is the series obtained in 1993. The eruption activity of Grand was relatively stable, centered about the mean, throughout the series. The first three-quarters of the 1994 series is similar to the 1993 series. However, the last one-quarter of the 1994 series shows a shift occurring, with IBE increasing significantly. A summary of the first 14 days of November 1994 is in **Table 2.**

Table 2. Grand Geyser intervals for the period November 1–14, 1994.

Minimum	Q1	Median	Mean	Q3	Maximum
444	595	635	665.3	741	919

n = 64 IBE

	90% Prediction Window	
Date	Minimum	Maximum
11/94	510	864

Clearly, a major change in geothermal forces resulted in a shift of Grand Geyser activity away from the long-term stability enjoyed between spring of 1993 and fall of 1994. It is apparent from Figure 5 that the change in Grand IBE stabilized between 11/14/94 and 3/27/95, resulting in a higher mean and median.

Boxplots

In order to examine the differences between the three years in more detail, side-by-side boxplots were constructed for the months of July and August. **Figure 7** contains the boxplots of the July data by year. To get a feel for how one might read these plots, think of standing above a histogram and looking down at the distribution being represented. The lower 'whisker' of the plot, connected to the box with a dashed line, is the minimum IBE. The lower border of the shaded box is the first quartile of the data. The line within the box is the position of the median. The upper border of the shaded box is the third quartile. The upper 'whisker' connected with a dashed line represents a maximum data value taking into consideration the possibility of extreme outlying observations. The boxplots for both 1994 and 1995 exhibit lines above the upper whisker. These represent extremely high values of IBE in comparison to the larger body of data.

The July boxplots in Figure 7 show the large change which occurred prior to July of 1995. July of 1993 and 1994 are similar in overall variability with medians of 499.5 and 503 minutes, respectively. The boxplot for July of 1995 shows an entirely different distribution with median of 626 minutes.

The August boxplots are exhibited in **Figure 8**. Note that the August 1994 distribution is showing the beginning of a shift away from the distribution of August 1993 IBE. This suggests that forces regulating eruptions of Grand Geyser were perhaps undergoing changes as early as August of 1994.

A Shift in Activity

Currently, there is indication that Grand Geyser's eruption activity is similar to that of late fall, 1994 through fall 1995. IBE obtained between late May 1996 and July 1, 1996 are summarized in **Table 3**.

Table 3. Grand Geyser intervals between late May 1996 and July 1, 1996.

Minimum	Q1	Median	Mean	Q3	Maximum
463	579	639.5	638.7	707	850

n = 64 IBE

Date	90% Prediction Window Minimum	Maximum
1995	497	782

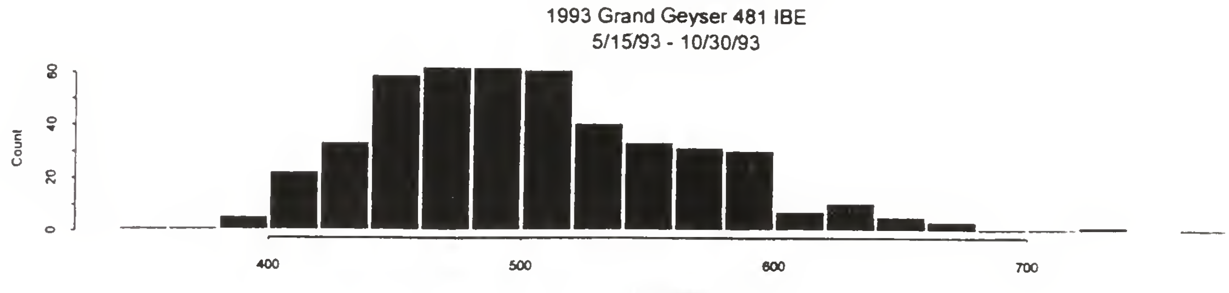
Conclusion

The change in activity of Grand Geyser between 1993 and 1995 is evidence of a major change in geothermal forces in the Upper Geyser Basin of Yellowstone National Park. There are other indicators which should also be noted here.

Castle Geyser was monitored during 1993, and remarkably, this was a period of time in which very few minor eruptions occurred. Castle Geyser's eruption activity was stable during 1993. However, the eruption of activity of Castle during 1995 was not stable. Castle Geyser was unpredictable and minor eruptions were frequent. The same forces acting on Grand probably were responsible for the extreme shift in activity of Castle Geyser between 1993 and 1995.

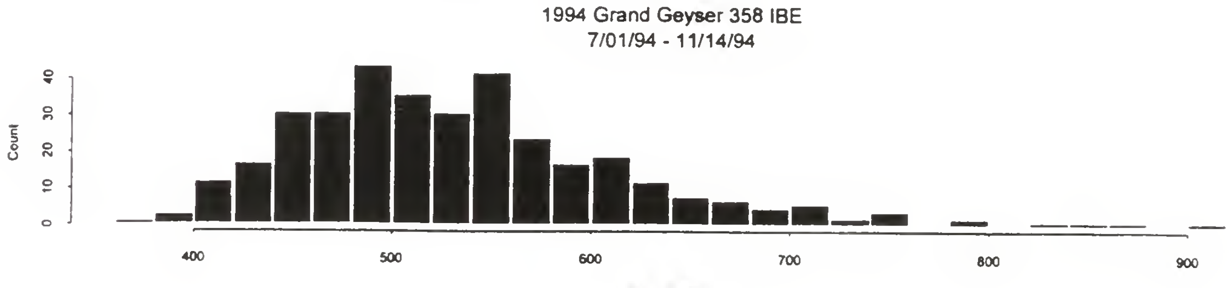
Daisy Geyser was monitored during 1995 and the average IBE of Daisy appeared significantly higher than IBE of preceding years. Again, there is a possibility that changes occurring in the geothermal features of the Upper Geyser Basin are all related to a major geothermal change.

Currently, the Castle Geyser data is under review, as is past data of Daisy Geyser IBE. Hopefully, this review will shed more light on the changes in the Upper Geyser Basin.



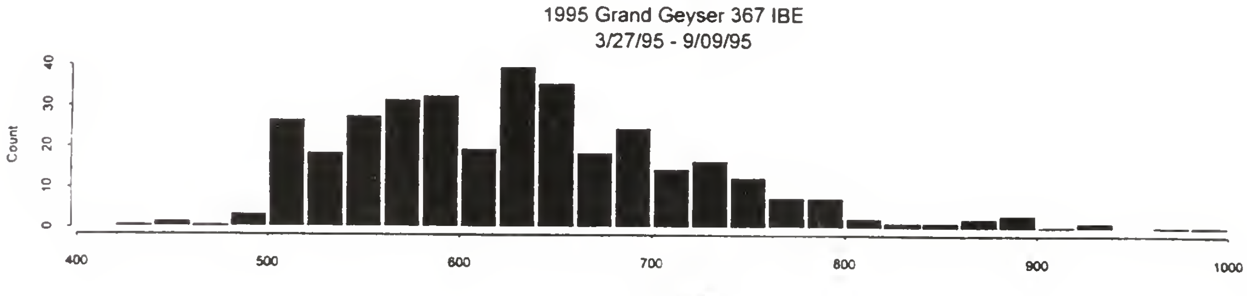
1993 Grand Geyser 481 IBE
5/15/93 - 10/30/93

Figure 1



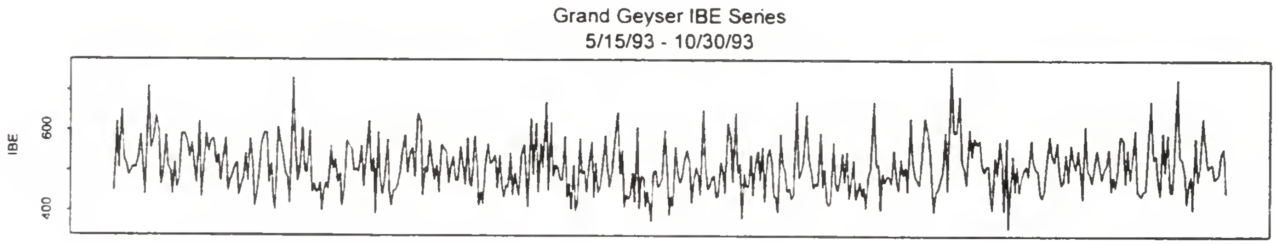
1994 Grand Geyser 358 IBE
7/01/94 - 11/14/94

Figure 2



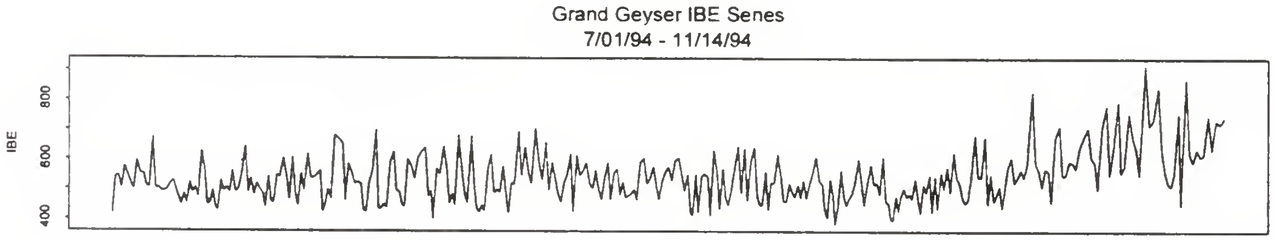
1995 Grand Geyser 367 IBE
3/27/95 - 9/09/95

Figure 3



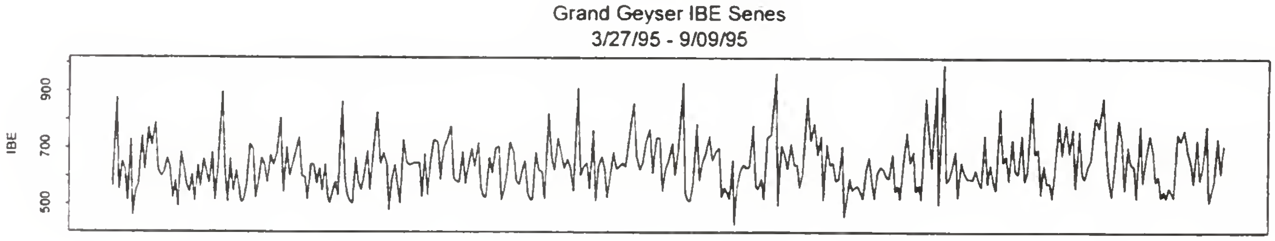
Grand Geyser IBE Series
5/15/93 - 10/30/93

Figure 4



Grand Geyser IBE Series
7/01/94 - 11/14/94

Figure 5



Grand Geyser IBE Series
3/27/95 - 9/09/95

Figure 6

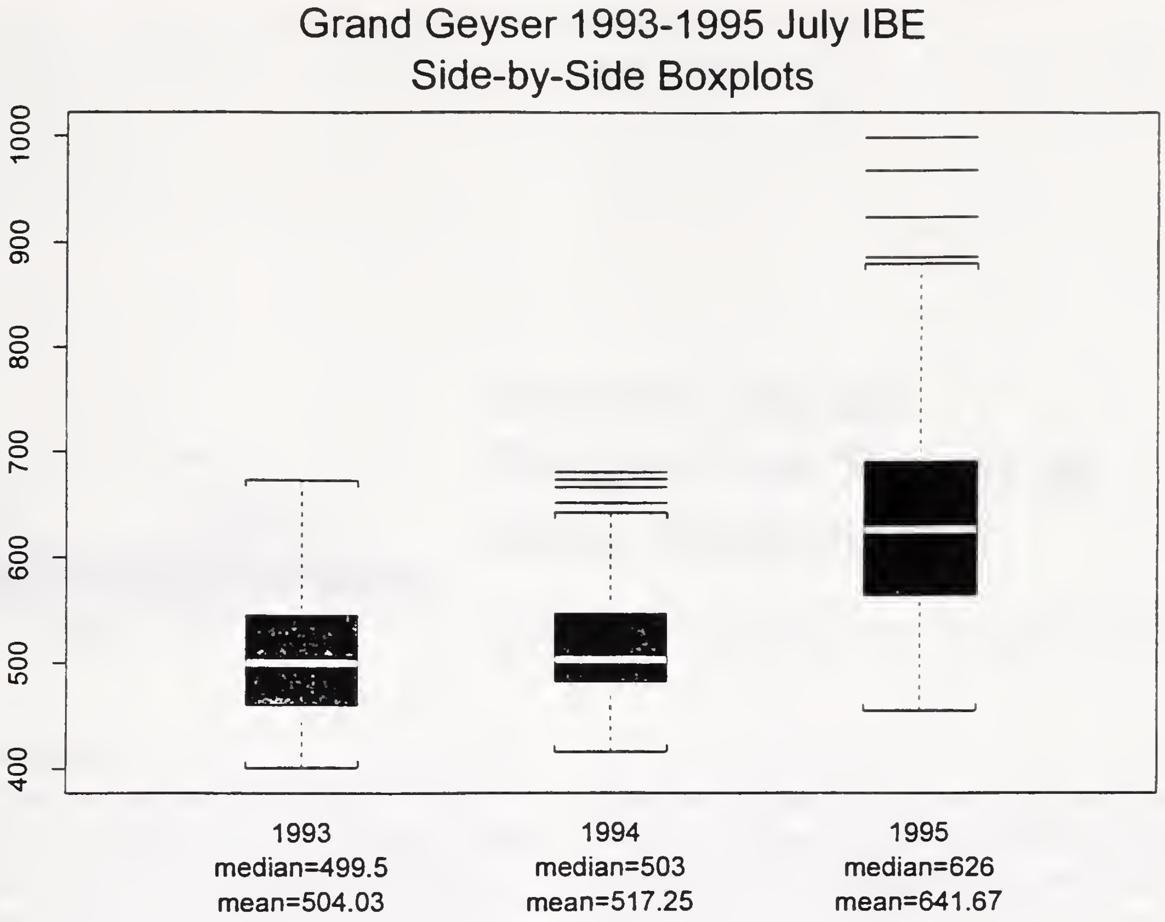


Figure 7

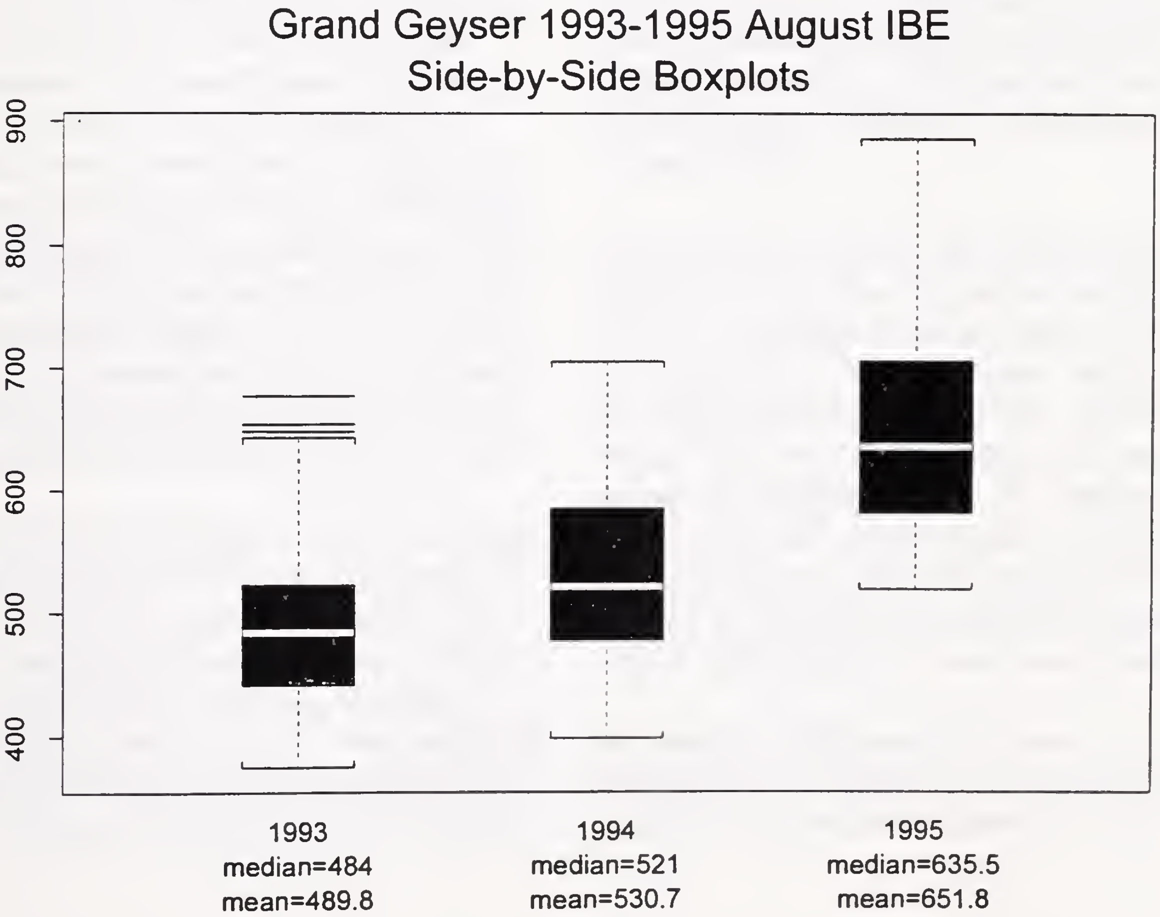


Figure 8

SPOUTER GEYSER: SUMMARY AND REPORT OF INITIAL INVESTIGATION

Introduction

This report serves as a summary of initial findings of eruption activity of Spouter Geyser. The study began as an advanced graduate research project in conjunction with the National Park Service and the University of Montana. In the spring of 1995, an electronic monitoring device was used to record the temperature in the runoff channel of Spouter Geyser. Eruption times and durations of eruptions were inferred from the data record and from personal observations. Preliminary findings indicate a strong relationship between durations of eruptions and intervals of times between eruptions (IBE), but this relationship fluctuates. The eruption behavior of Spouter Geyser was also significantly affected by the earthquake swarms during mid-June of 1995.

Spouter Geyser is located in Black Sand Basin on the east side of Iron Creek. The geyser is also east of Sunset Lake and Rainbow Pool, both of which are located on the west side of Iron Creek. When monitoring of Spouter Geyser began, several changes were beginning to show in the thermal features of Black Sand Basin. The level of thermal waters in Rainbow Pool had dropped 0.75 meters by early June, and by mid-June the bacterial life creating the beautiful colors surrounding the pool had died out. Sunset Lake was in heavy overflow and bursting to unprecedented heights of an estimated 8-10 meters. During the previous year, 1994, Sunset Lake was showing signs of boiling and bursting, yet this activity was nowhere near the magnitude of activity observed in 1995.

Since there were no previous long-term data records available, the original purpose of this project was to build a base for future reference and comparative studies. Monitoring of Spouter Geyser began on 5/17/95 and, with the exception of the loss of a single day, data was continuous through 9/21/95. The data record includes 549 IBE and durations of Spouter Geyser eruptions. The main purpose of this report is to document the activity of Spouter Geyser and discuss some preliminary analyses.

Summaries of IBE and Durations

A summary of the intervals of time between eruptions is presented in **Figure S1**. The histogram shows the approximate distribution of the 549 IBE. The distribution is not symmetric with skewing toward longer IBE. This shape of distribution is similar to recent distributions of Grand Geyser and Great Fountain Geyser. The summary statistics are presented in **Table 1** (times are in minutes).

Table 1. Summary statistics for Spouter Geyser intervals, 1995.

Minimum	Q1	Median	Mean	Q3	Maximum	St.Dev.
166	270	318	327.5	386	652	86.43

Unfortunately, there is no long-term data from past years and it is not possible to discuss the possibility of a change from the previous year.

A summary and histogram representing the *durations* of eruptions is presented in **Figure S2**. This distribution is also not symmetric with skewing to the right. The summary statistics are presented in **Table 2** (times are in minutes).

Table 2. Summary statistics for durations of Spouter Geyser eruptions, 1995.

Minimum	Q1	Median	Mean	Q3	Maximum	St.Dev.
42	90	112	118.5	146	290	43.21

Given the average and median duration of approximately two hours, Spouter Geyser is seen annually by thousands of visitors. In fact, the median duration of 112 minutes and the median IBE of 318 minutes suggest that Spouter is in eruption almost one-third of the time.

Series of IBE and Durations

Figure S3 is a plot of the series of IBE versus the actual time of the eruption. The gap at the end of the series is due to a loss of data. There does not appear to be any significant pattern within the series. The series in this time period beginning on 5/30/95 and continuing to 6/07/95 is inconsistent with the remainder of the series. The shorter IBE throughout the series do not exist during the nine-day time period beginning in late May. Immediately following this period of time is the longest recorded IBE of record.

Figure S4 is a plot of the series of durations versus the actual time of eruption. This series also indicates a temporary change in activity during the period of time from 5/30/95 to 6/07/95. That both IBE and duration series show a similar anomaly during the same period of time suggests a possible relationship between IBE and duration. This will be discussed in detail later in this report.

Often for purposes of prediction, it is worth asking if preceding IBE can offer any indication about upcoming eruptions. If so, consecutive observations within the series would most likely exhibit autocorrelation. **Figure S5** is the autocorrelation function of the series. There does not appear to be any significant correlation between neighboring data points.

To examine possible long-term trends, seven-day moving averages and seven-day running medians were constructed. The results are exhibited in **Figures S6** and **S7**, respectively. The overall shift to decreased IBE during early June is dramatic. Shifts to decreased IBE also occur again in late-June, late-July, and late-August. These shifts generally occurred during times of intense seismic activity within the Yellowstone region.

Relationship Between Preceding Duration and IBE

A review of figures S3 and S4 indicate a close relationship between duration and IBE. If one assumes a relatively constant source of heat and water, it is reasonable to assume that longer durations of eruptions would deplete the system, leading to longer IBE, whereas shorter durations of eruptions would lead to shorter IBE. **Figure S8** is a scatterplot of IBE versus preceding duration. There is a strong positive relationship between the two variables. Pearson's correlation coefficient is 0.981, suggesting a linear relationship. The least-squares regression line is superimposed on the scatterplot and given as:

IBE = 96.29 + 1.95*Preceding Duration (minutes)

With a slope of 1.95, we give the interpretation that for each additional minute of eruption duration, we can expect to wait an additional 1.95 minutes to the next eruption. However, with reference to the straight line, the data points appear to be slightly curvilinear. Several transformations of the data were attempted. A square root transformation of both variables resulted in removal of the major curvature. The scatterplot, line and regression are presented in **Figure S9**. The transformed regression equation is given as:

Sqrt(IBE) = 5.26 + 1.18*sqrt(Preceding Duration)

While there is a definite improvement in linearity, it appears to be at the expense of a slight increase in variability for the smaller data values. Yet in general, the transformation does a better job of forcing the higher valued data pairs into the general linear trend. For the remainder of this report, analysis and discussions regarding the relationship between preceding duration and IBE are based upon the transformed data.

The Regression Residuals

A time series plot of the residuals can often point out any obvious correlation of these error terms over time. **Figure S10** is a time series plot of the residuals (error terms) obtained from regressing the first 450 transformed data pairs. There are some obvious trends in the time series of these residuals. We will examine these trends separately. Keeping in mind that a residual is the error which remains when the regression line (predicted) IBE value is subtracted from the actual observed IBE, it is clear that the error terms are positive in the beginning of the series and negative at the end of the series. The regression line tends to underestimate the observed IBE early in the series and overestimate the observed IBE late in the series.

Throughout the middle of the series, the residuals appear stable, with a cyclical and slight decreasing trend. The residuals tend to increase and decrease over short periods of time. The long-term trend might be indicating a change in the slope over time. For instance, if the slope is decreasing, then it is highly possible that there is a change occurring in the geothermal forces regulating eruptions of Spouter Geyser. Since we are assuming that IBE depends upon the preceding duration, a decreasing slope over time could be interpreted as an increased recharge rate. Originally, a one-minute decrease in duration might mean a two-minute increase in IBE. Later, a one-minute increase in duration might mean a one-and-one-half-minute increase in IBE. The long-term trend could be indicating a seasonal component of Spouter Geyser.

During the spring, increased cooler near-surface water may mix with thermal waters, increasing IBE. As surface waters become depleted, activity may depend more on preheated thermal waters entering the system, decreasing IBE.

There is a striking difference in the residuals of the first 100 data pairs in comparison to the remaining residuals of the time series. The first 100 residuals are the result of the regression involving the data pairs through approximately 6/10/95. This is the same time period when a major shift begins to appear in the IBE series of Figures S6 and 7. It is probably not a coincidence that early-June through mid-June was a time of increasing local seismic activity. Swarms of earthquakes might loosen partially sealed fractures, providing an improved conduit of heat. If injection of heat into the geyser basins increases, it is reasonable to assume that critical high temperatures initiating eruptions would be reached sooner.

The time series of the residuals also shows some short-term periodic cycles. To assess the possibility of such periodic behavior, a periodogram was constructed. **Figure S11** is the resulting plot of the spectrum (decibels) versus the Fourier frequency. Ignoring the first spike, which represents the series of residuals as one complete period, there is a secondary spike immediately to the right. The approximate Fourier frequency is 0.02325, which translates to a cycle of approximately 43 eruptions. Keeping in mind that this is the periodogram of the residuals, there is an implication here that the mechanics driving the geyser system may slowly cycle over 40+ eruptions. At this time, no interpretation will be given to explain this possible phenomena, although there may be a cyclical pattern of the system as evidenced in the middle of the residual series of **Figure S10**. This documentation of a periodic trend will serve as a reference in follow-up monitoring of Spouter Geyser.

The Slope

Since the slope might yield information pertaining to changes in the geothermal activity of Spouter Geyser, it was desirable to examine the behavior of the slope as a sequence over periods of time. Outliers in the horizontal direction (preceding duration) can strongly influence the slope of the least-squares line. In an attempt to smooth out and reduce the chance of a strong influence by a few data points, regression slopes of the transformed data were constructed over sequences of nine days. Thus, the first slope obtained would be the regression slope of the data from 5/17/95 through 5/25/95. The second slope would then be obtained from 5/18/95 through 5/26/95. In such a manner a series of 'running' slopes was constructed. This series is plotted in **Figure S12**. Not surprisingly, there is a drastic shift to a decreased slope during mid-June. As suggested earlier, this period of time is associated with the beginning of intense seismic activity. Again there is evidence supporting the hypothesis of an increased injection of heat into Black Sand Geyser Basin.

The possibility of over-smoothing the data using the nine-day series resulted in a final run of regressions over a seven-day series. This sequence of running slopes is shown in **Figure S13**. The major trends highlighted in the nine-day sequences are still apparent. In addition to the inferred influence of seismic activity, there are two other dramatic inconsistencies in showing in both the nine- and seven-day running slope series. There are periods of decreasing slopes during late-July and again during mid-September. Comments regarding these periods of time are left to the park geologist.

Conclusion

An examination of the Spouter Geyser data series, both duration and IBE, suggest a random realization of a bivariate process. It can be concluded based on the analysis presented in this report that the distribution of IBE and duration are not bivariate normal distributions.

There is a strong positive correlation between preceding duration and IBE. The linearity is improved through a square root transformation. Time-series plots of moving averages and medians of IBE, residuals, and running slopes, strongly support the hypothesis that Spouter Geyser reacted to the major seismic events which occurred in mid-June and the later summer months.

In 1996, Spouter Geyser is to be monitored continuously. An report in the near future will reference this present report. For the first time, we hope to document and determine long-term changes and the direction of such changes.

Spouter Geyser 549 IBE Mean=327.5 StDev=86.43
Min=166 Q1=270 Median=318 Q3=386 Max=652

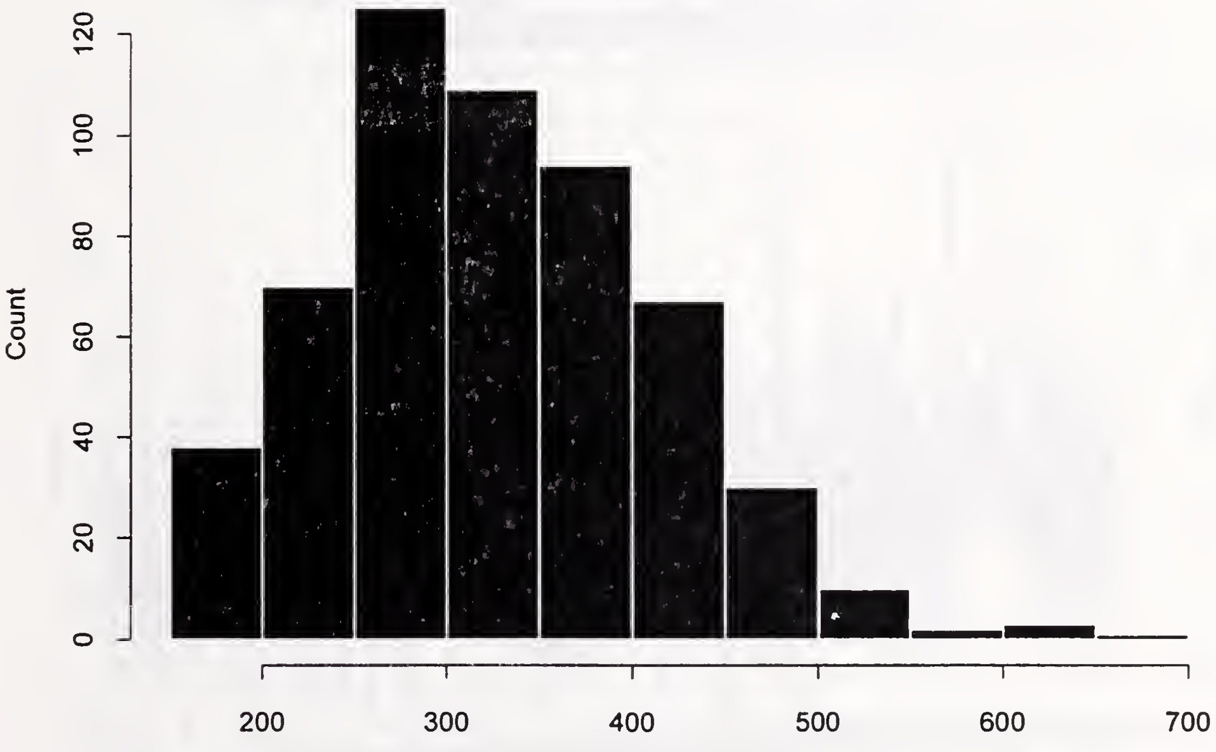


Figure S1

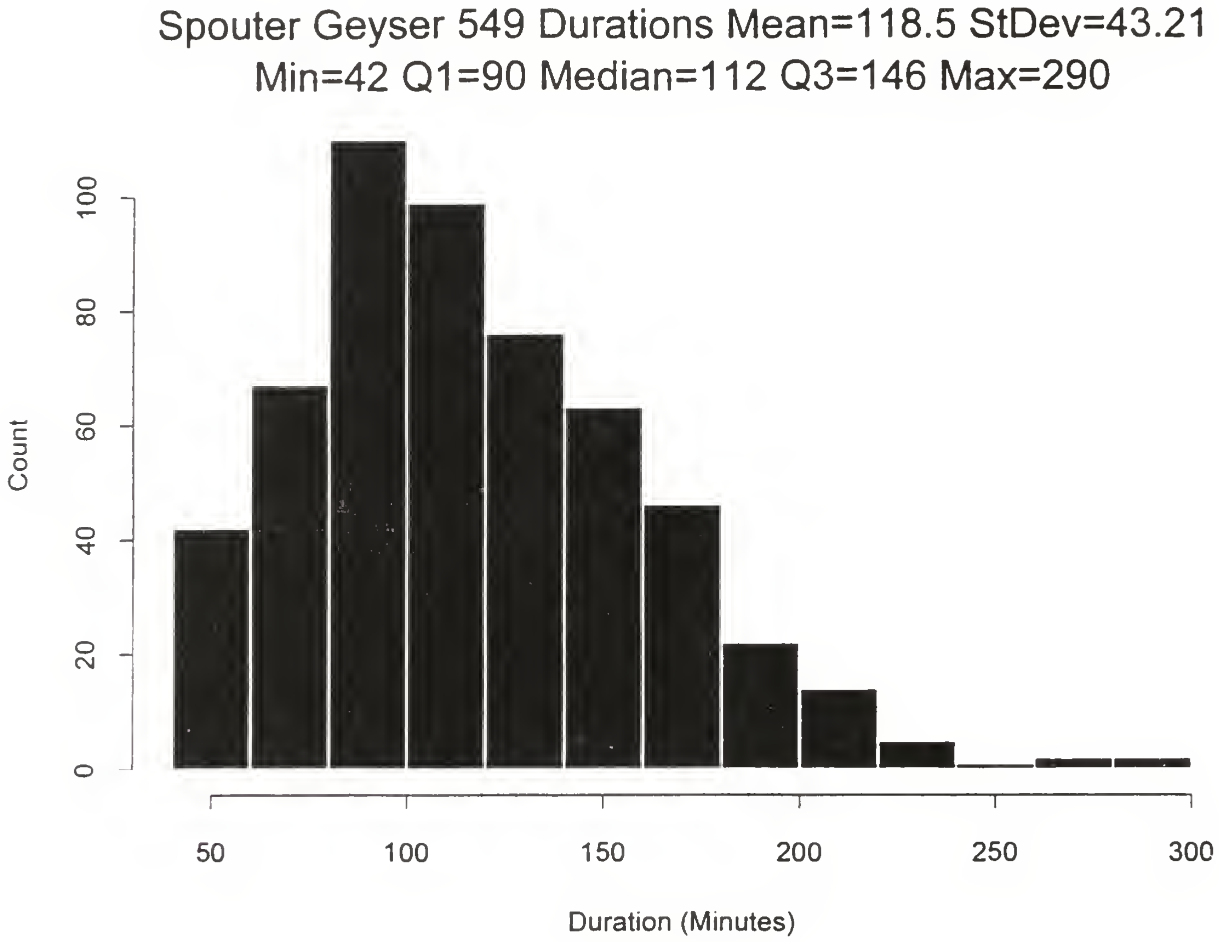


Figure S2

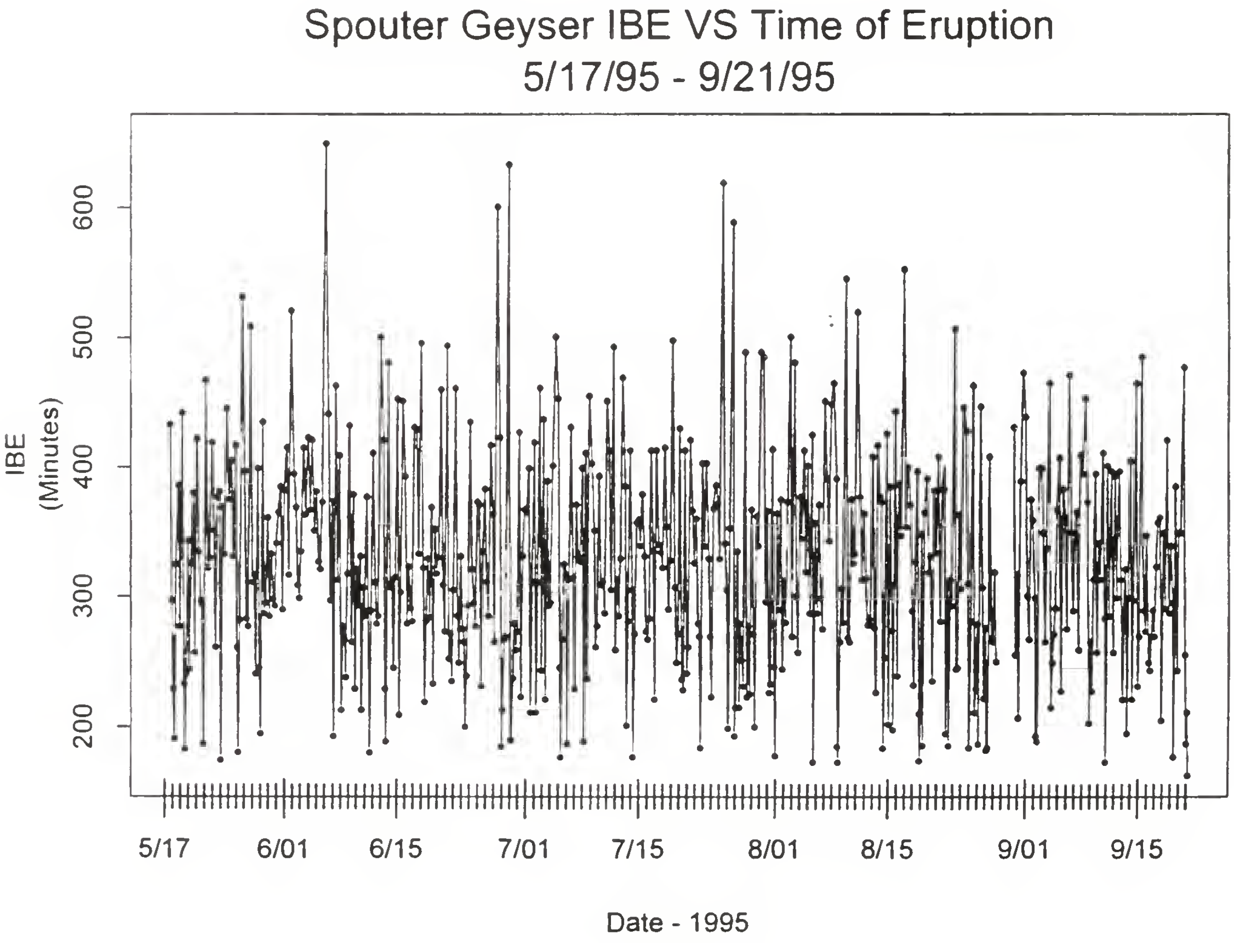


Figure S3

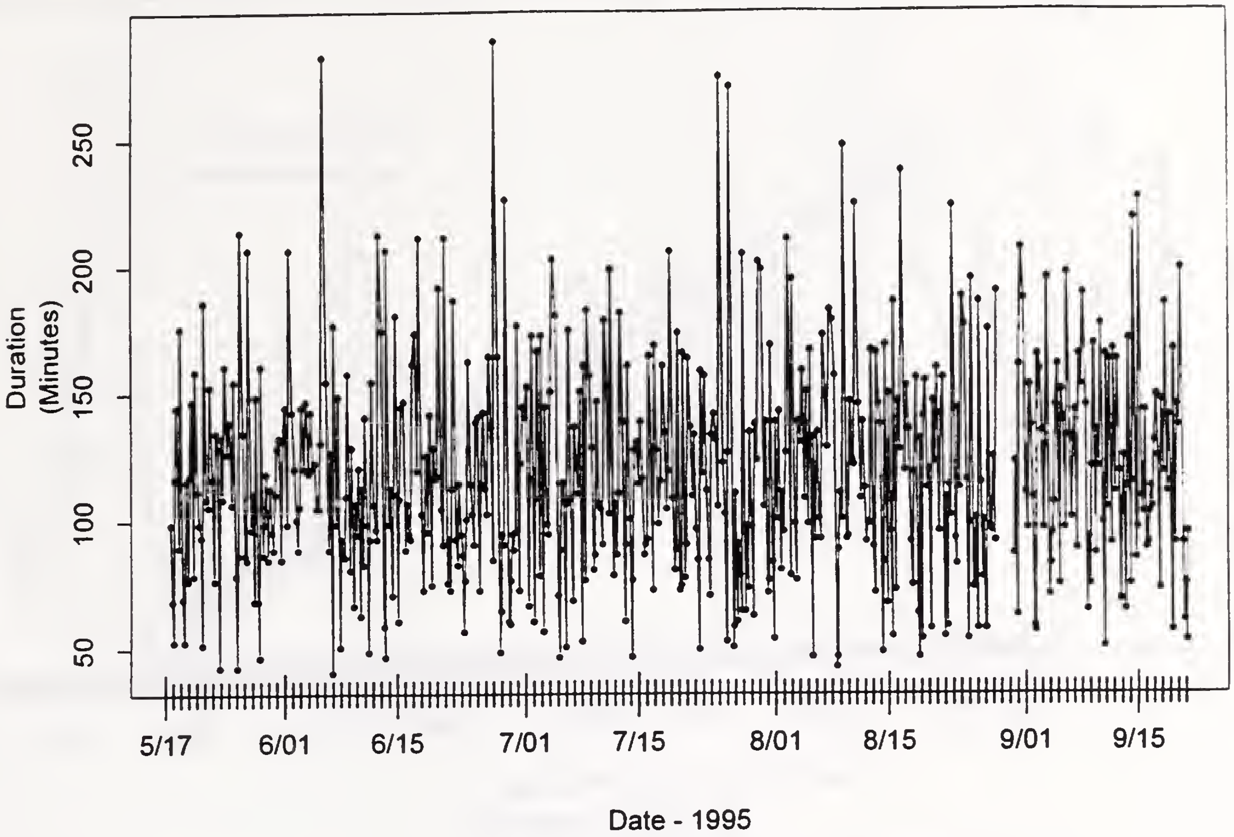
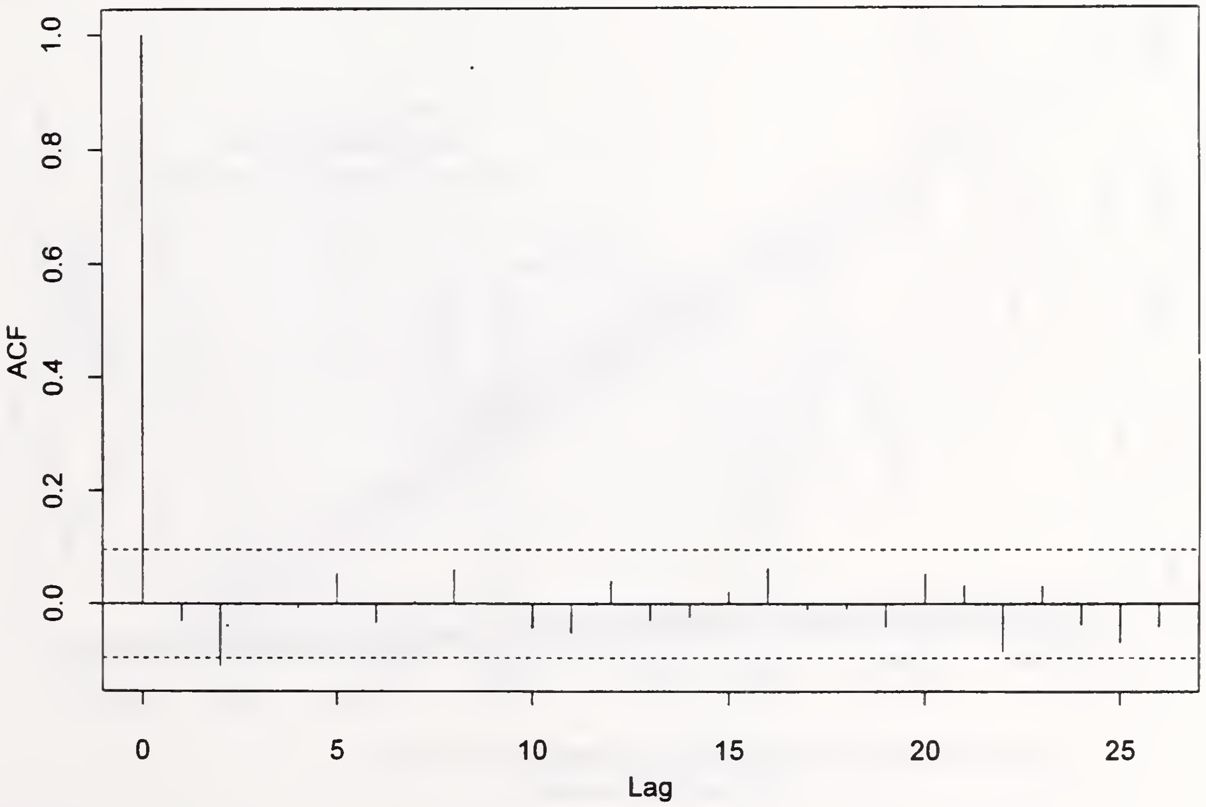

Spouter Geyser Duration VS Time of Eruption
5/17/95 - 9/21/95

Figure S4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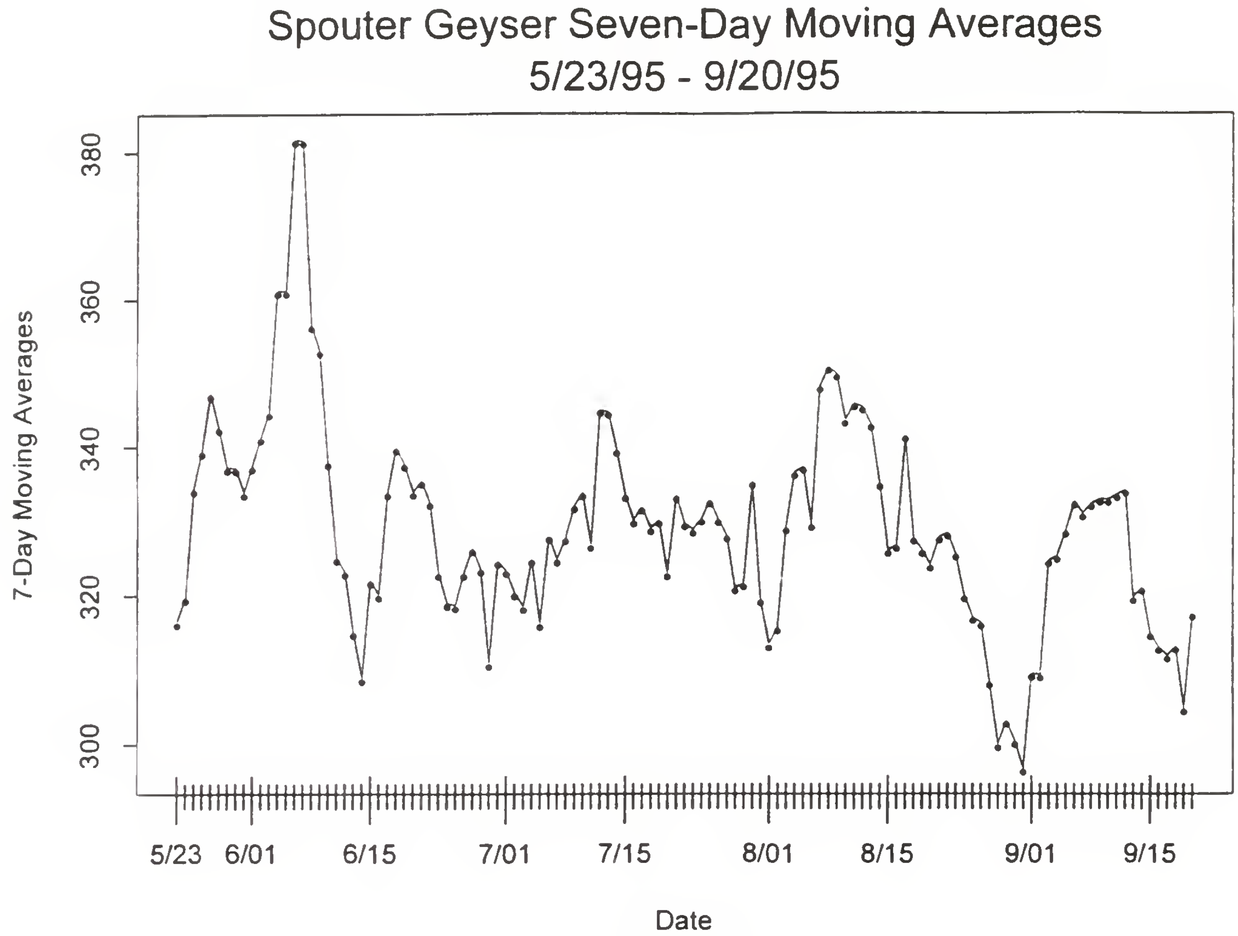


Figure S6

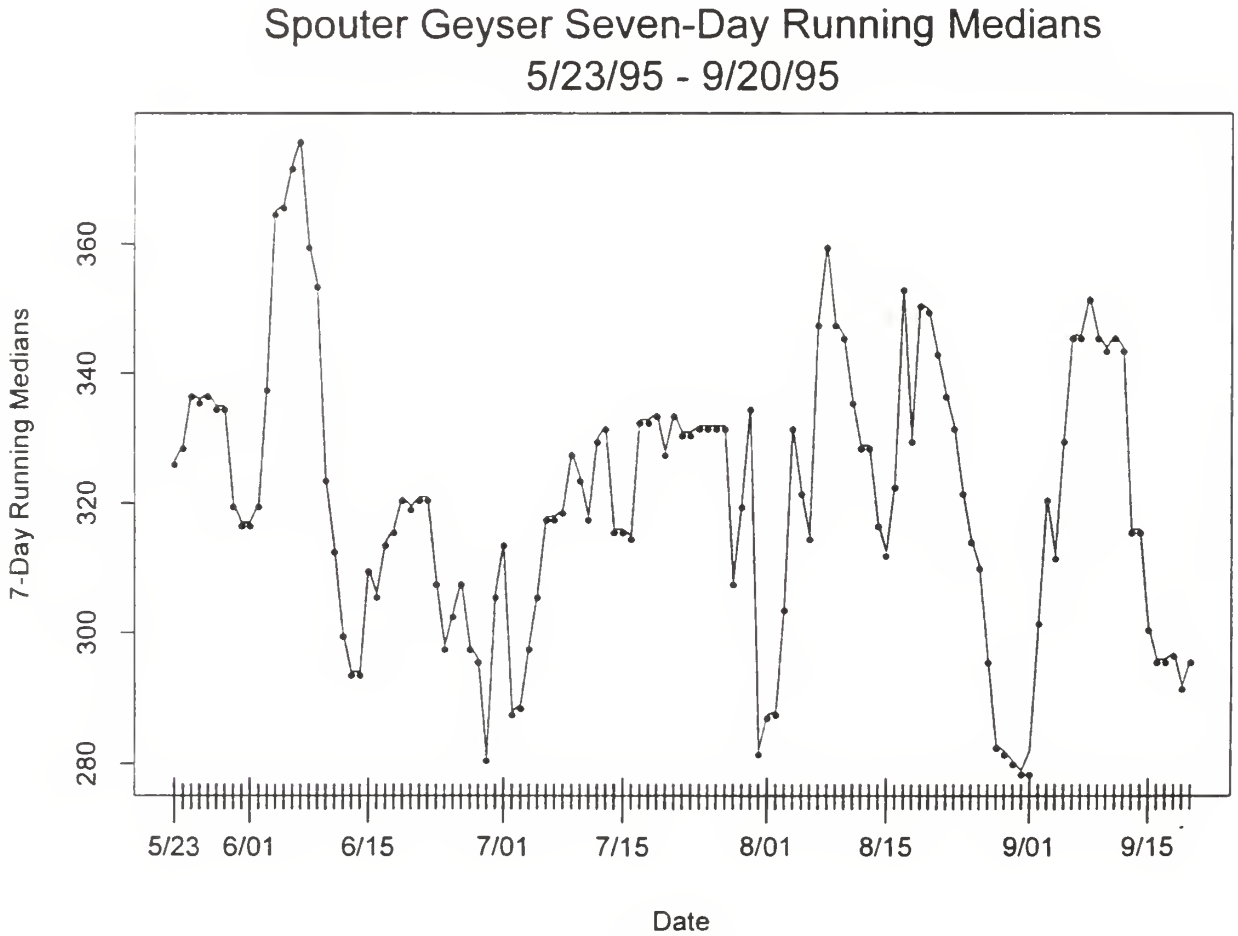


Figure S7

Spouter Geyser IBE VS Preceding Duration
548 Data Pairs

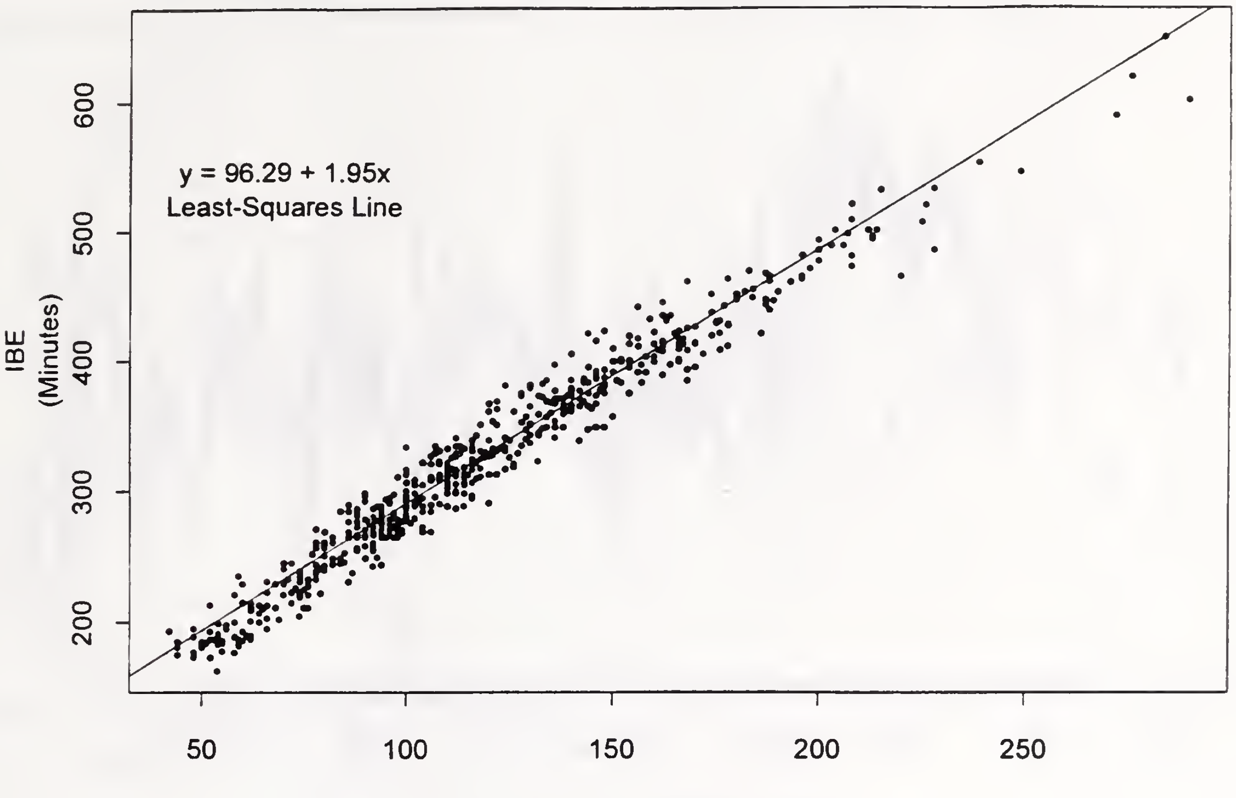


Figure S8

Spouter Geyser IBE VS Preceding Duration
Square Root Transformation 548 Data Pairs

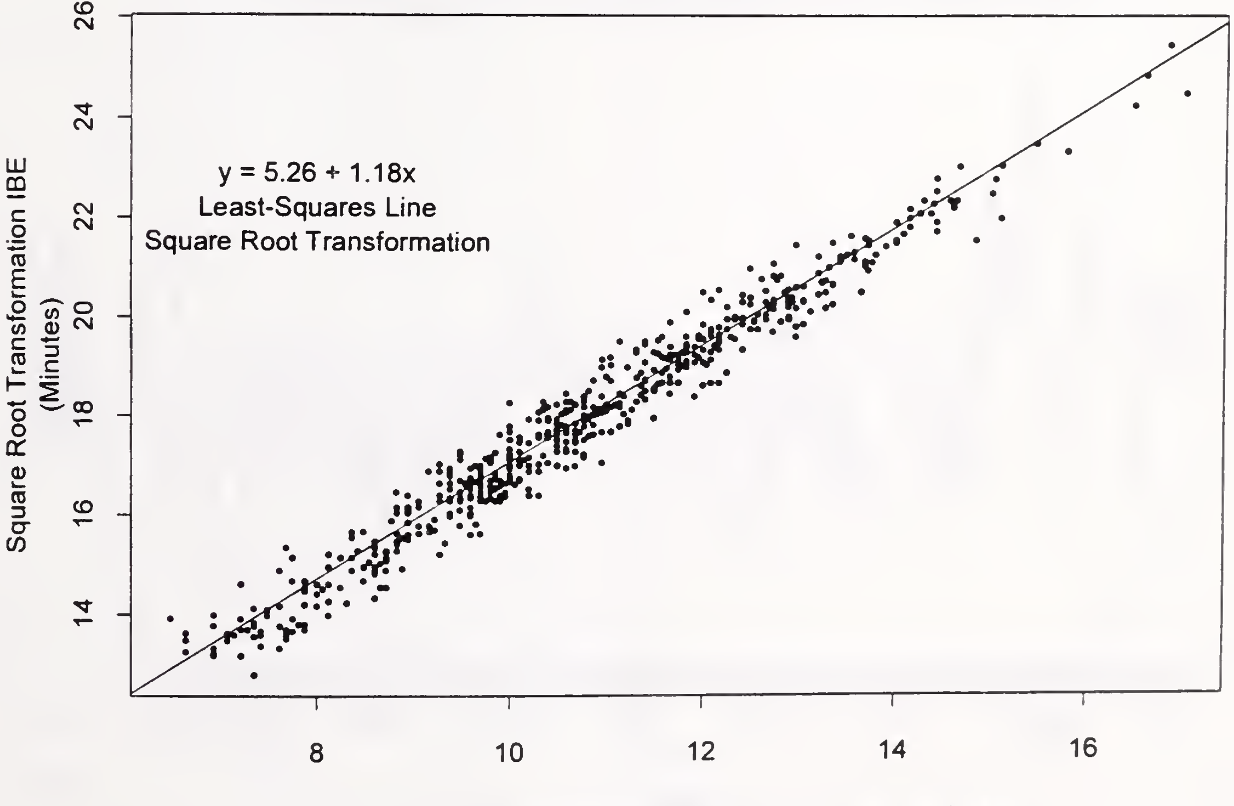


Figure S9

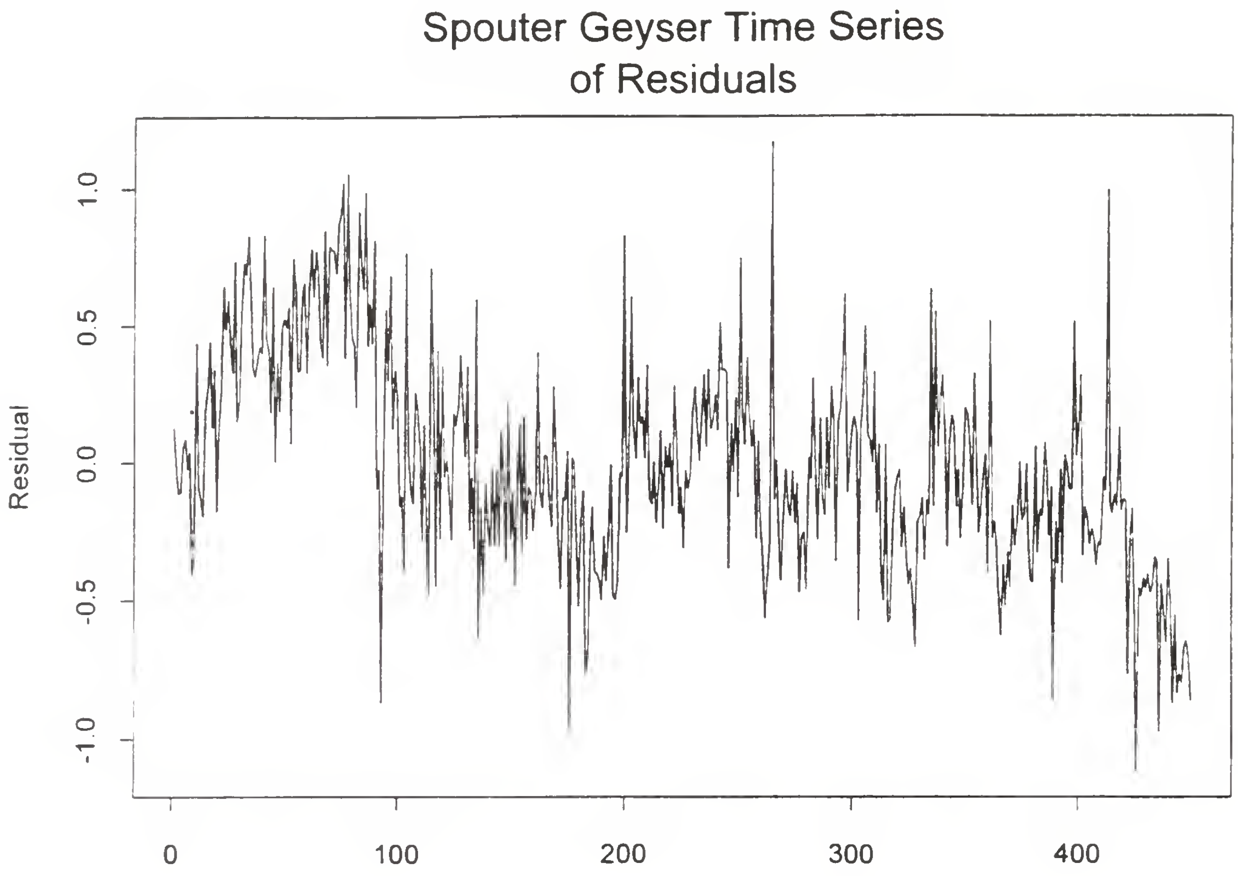


Figure S10

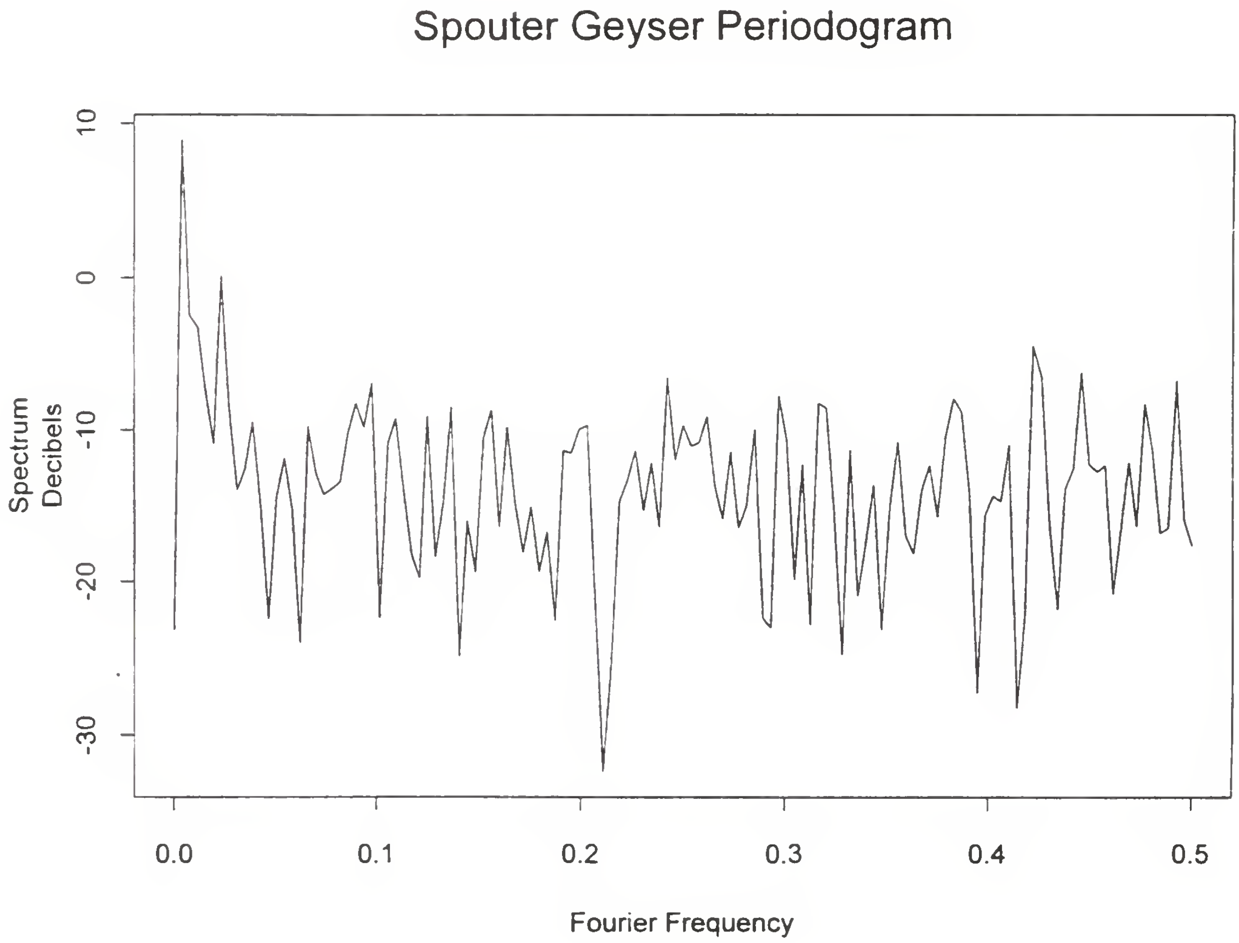


Figure S11

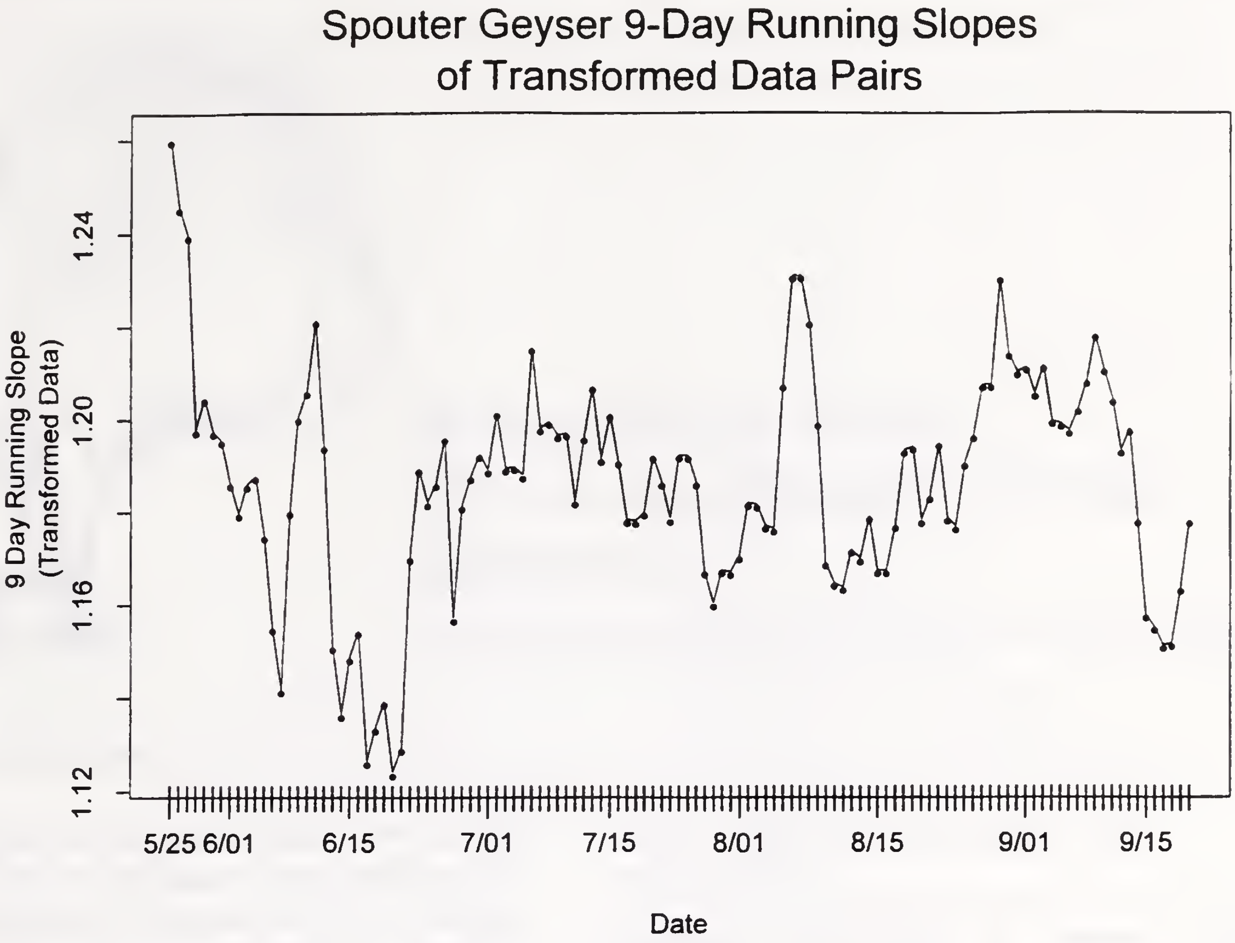


Figure S12

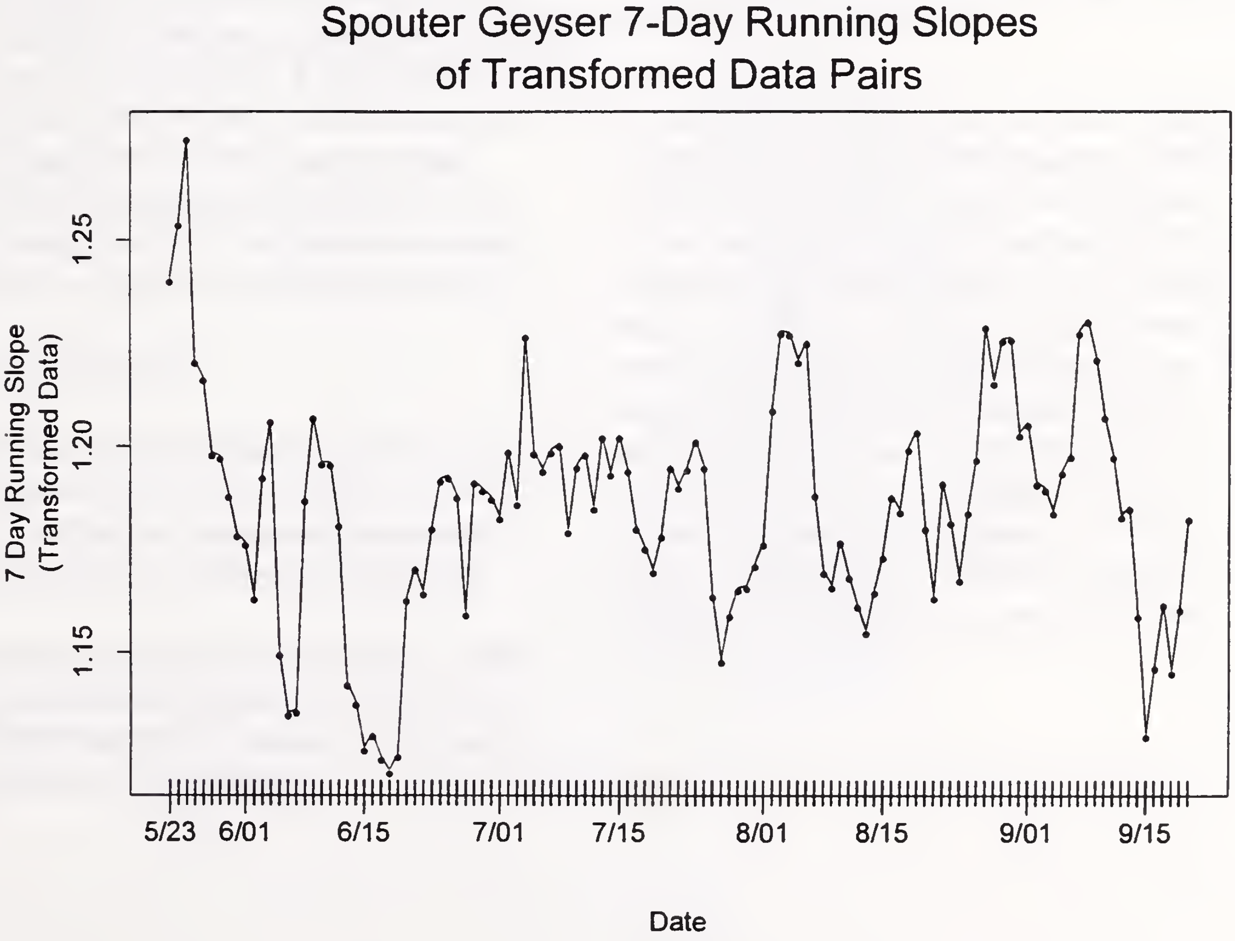


Figure S13

NORRIS GEYSER BASIN: ECHINUS AND MONARCH GEYSER SUMMARIES

INTRODUCTION

Between late spring and fall of 1995 (5/15/95 - 10/02/95), temperature meters collected data to monitor and study the activity of Echinus and Monarch geysers located in the Norris Geyser Basin of Yellowstone National Park. 1995 was the second year in which monitoring equipment was available. A previous report (Thompson 1995) reflects results of the monitoring during 1994. This report contains summaries and comments pertaining to the data collected in 1995, with some comments regarding comparisons with the 1994 data.

ECHINUS GEYSER

Figure E1 is the distribution of 2013 intervals of time between eruptions (IBE) where the interval is the time in minutes between the beginning times of consecutive eruptions.

A summary of the IBE is presented in **Table 1**. For comparison purposes, during 1994, 1663 IBE resulted in a median of 79 minutes and a mean of 94.51 minutes.

Table 1. Summary statistics for Echinus Geyser intervals, 1995.

Minimum	Q1	Median	Mean	Q3	Maximum	St.Dev.
15	68	81	80.11	86	360	23.37

n = 2103

The activity of Echinus can fluctuate wildly in response to basin-wide disturbances, seismic activity and, probably, other undetermined forces. Generally, Echinus eruptions are fairly consistent with IBE within the 70-80 minute range. In order to examine and summarize this more general activity, all IBE greater than 100 minutes and less than 50 minutes were removed from the data. The distribution of the remaining IBE is given in **Figure E2**. The summary is presented in **Table 2**. For comparison, during 1994, 1428 IBE resulted in a median of 77 minutes and a mean of 75.49 minutes.

Table 2. Summary statistics for 1995 Echinus Geyser eruptions, adjusted by removing all IBE greater than 100 minutes and less than 50 minutes.

Minimum	Q1	Median	Mean	Q3	Maximum	St.Dev.
51	68	81	77.2	85	99	10.74

n = 1856

The distribution of this more general activity suggests activity of a bimodal nature. However, as will be discussed shortly, this bimodal distribution was not generated in a random manner.

Figure E3 is the series of median IBE by day. Gaps in the series are due to missing data or few available data points during specific days. **Figure E4** is the series of mean IBE by day.

The fluctuating patterns in both figures suggest there are times when Echinus IBE are temporarily stable at shorter intervals or temporarily stable at longer intervals. The bimodal distribution observed in Figure E2 is clearly the result of these temporary fluctuations in Echinus IBE. This point should not be lost on the reader. Overall, Echinus IBE are not random about a measure of central tendency. However, the behavior within the individual modes may very well be random about central measures within each mode.

Between approximately 8/01/95 and 8/15/95, Norris Geyser basin experienced a local disturbance. Echinus responded to this disturbance this is clearly represented in both Figures E3 and E4.

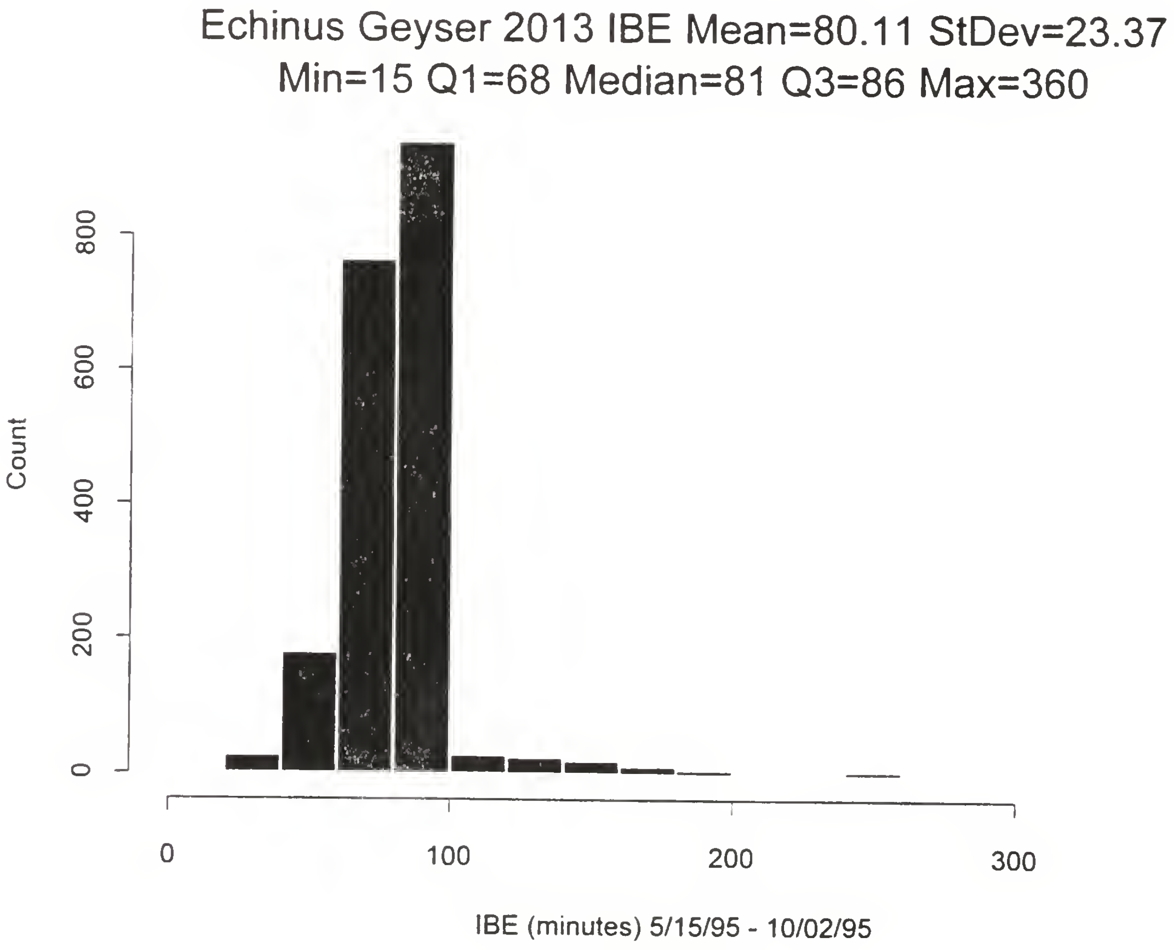
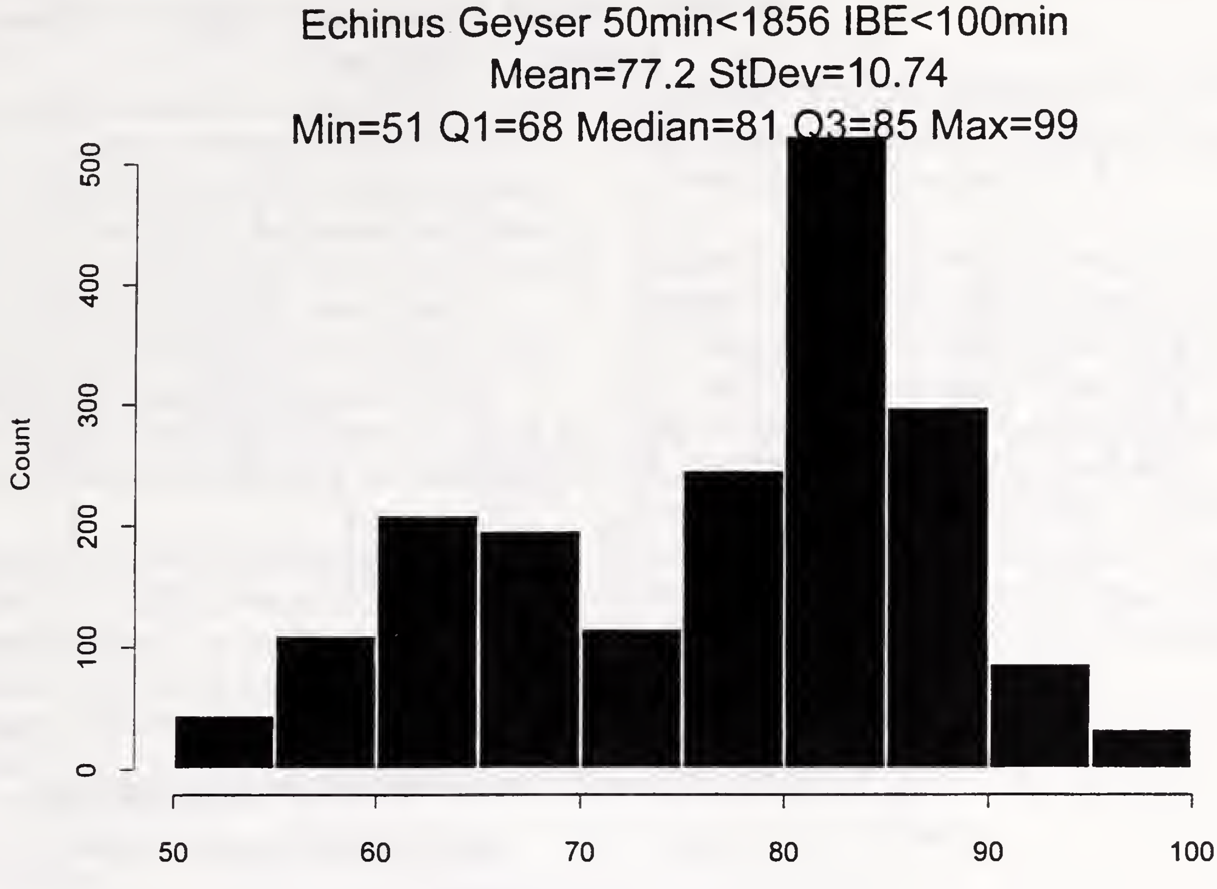
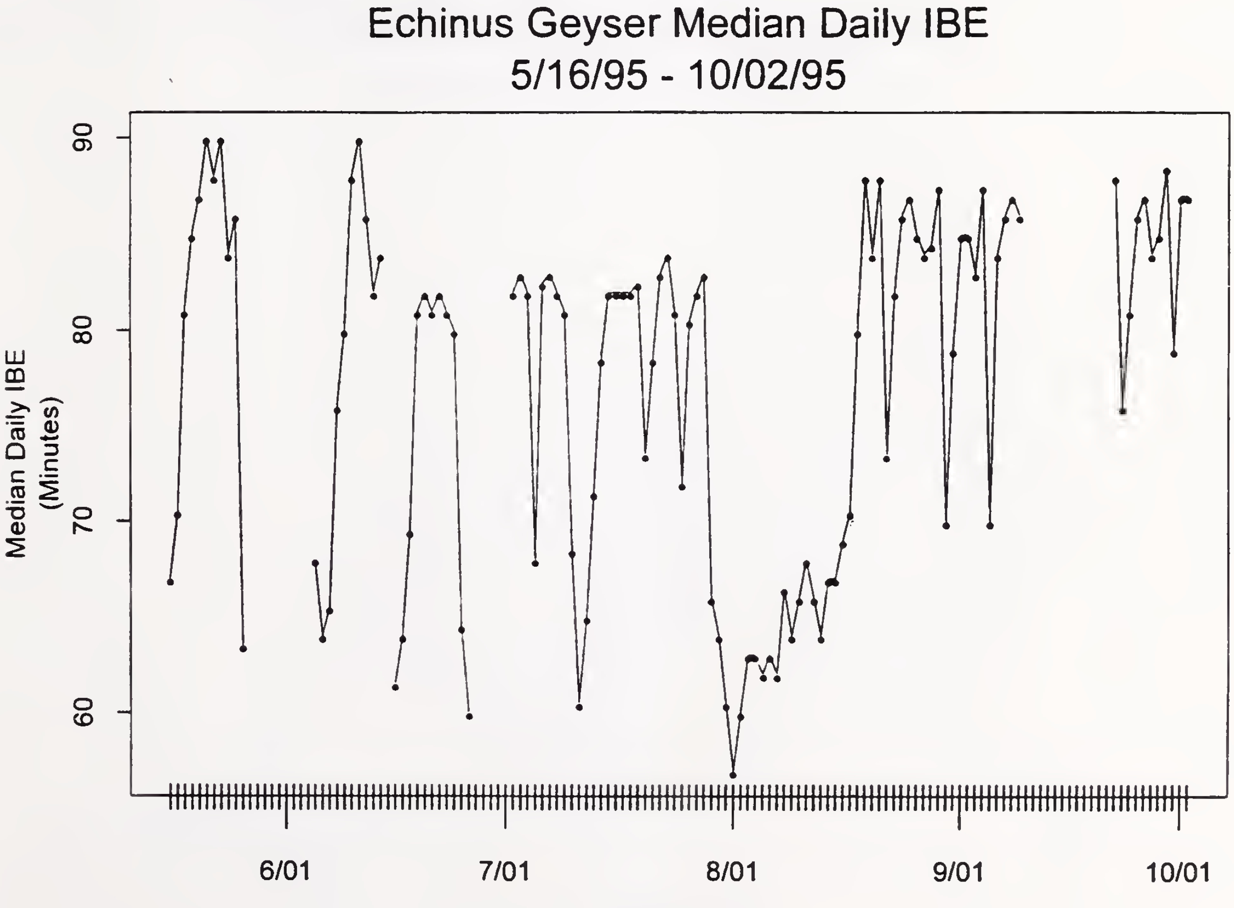


Figure E1



IBE (minutes) 5/15/95 - 10/02/95
Figure E2



Date - 1995
Figure E3

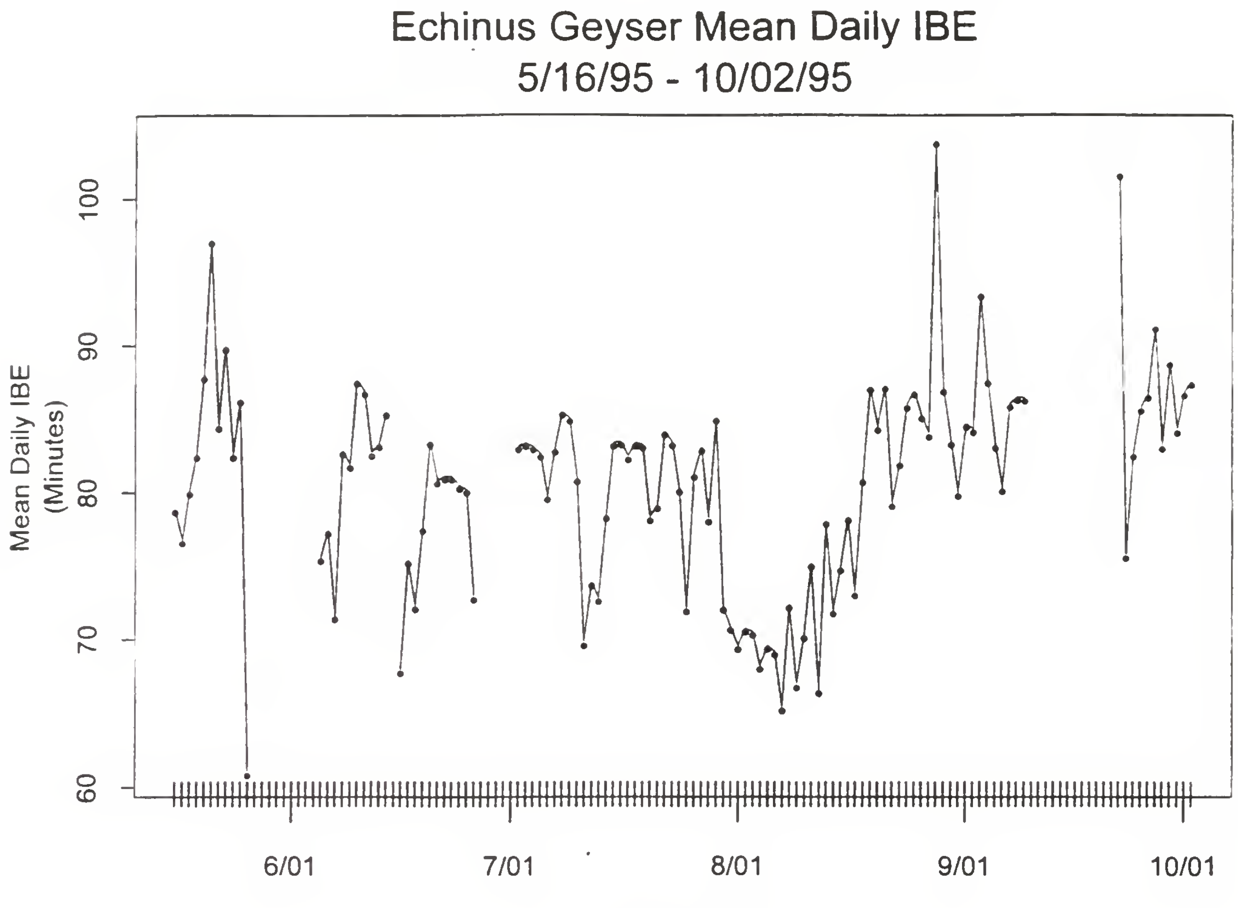

Echinus Geyser Mean Daily IBE
5/16/95 - 10/02/95
Mean Daily IBE (Minutes)
60
70
80
90
100
6/01
7/01
8/01
9/01
10/01
Date - 1995

Figure E4

MONARCH GEYSER

As in 1994, Monarch Geyser exhibited several types of activity. The activity varied from low-temperature overflows, to mid-temperature boils, and higher-temperature eruptions. It is difficult to sort out any one of these from the other when examining the data record. In 1995, as in 1994, the temperature record was searched for temperatures exceeding 35° C. Such temperatures defined the beginning of an event. These events make up the data frame.

Figure M1 is a histogram depicting the distribution of 1973 IBE, where IBE refers to interval between events. There is a strong bimodal tendency with perhaps even a trimodal tendency. The overall summary is presented in **Table 3**.

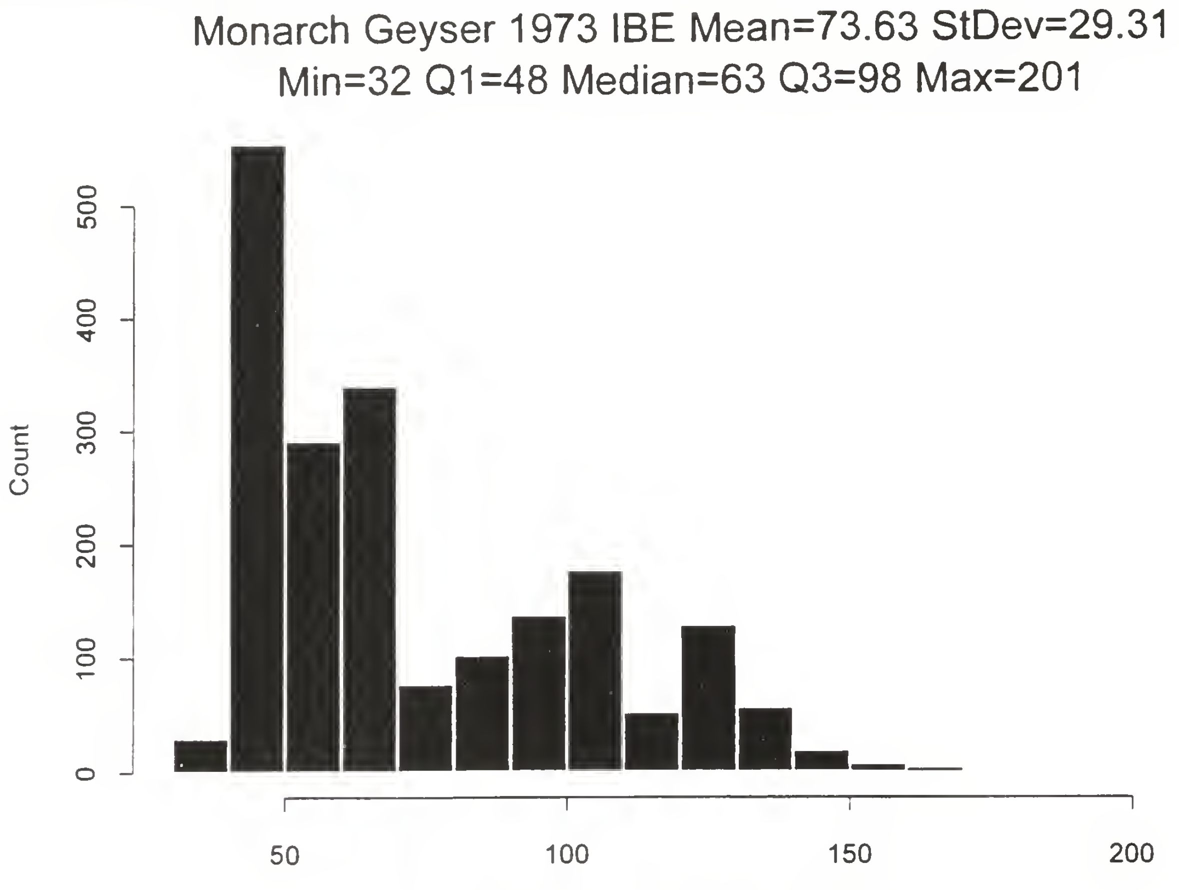
Table 3. Summary statistics for Monarch Geyser intervals, 1995.

Minimum	Q1	Median	Mean	Q3	Maximum	St.Dev.
32	48	63	73.63	98	201	29.31

n = 1973

Figures M2 and M3 are the median and mean daily series. Monarch also shows response to the early August disturbance.

Figures E-M1 and E-M2 are overlays of both Echinus and Monarch median and mean daily IBE, respectively. In both figures, the Monarch series is denoted with a dashed line. Of interest is that both geysers appear to respond similarly to whatever mechanisms create change in the Norris Geyser Basin. At times both geysers respond simultaneously to change while at other times changes in Echinus lag behind changes in Monarch by no more than a day.



IBE (Minutes) 6/05/95 - 10/02/95
Figure M1

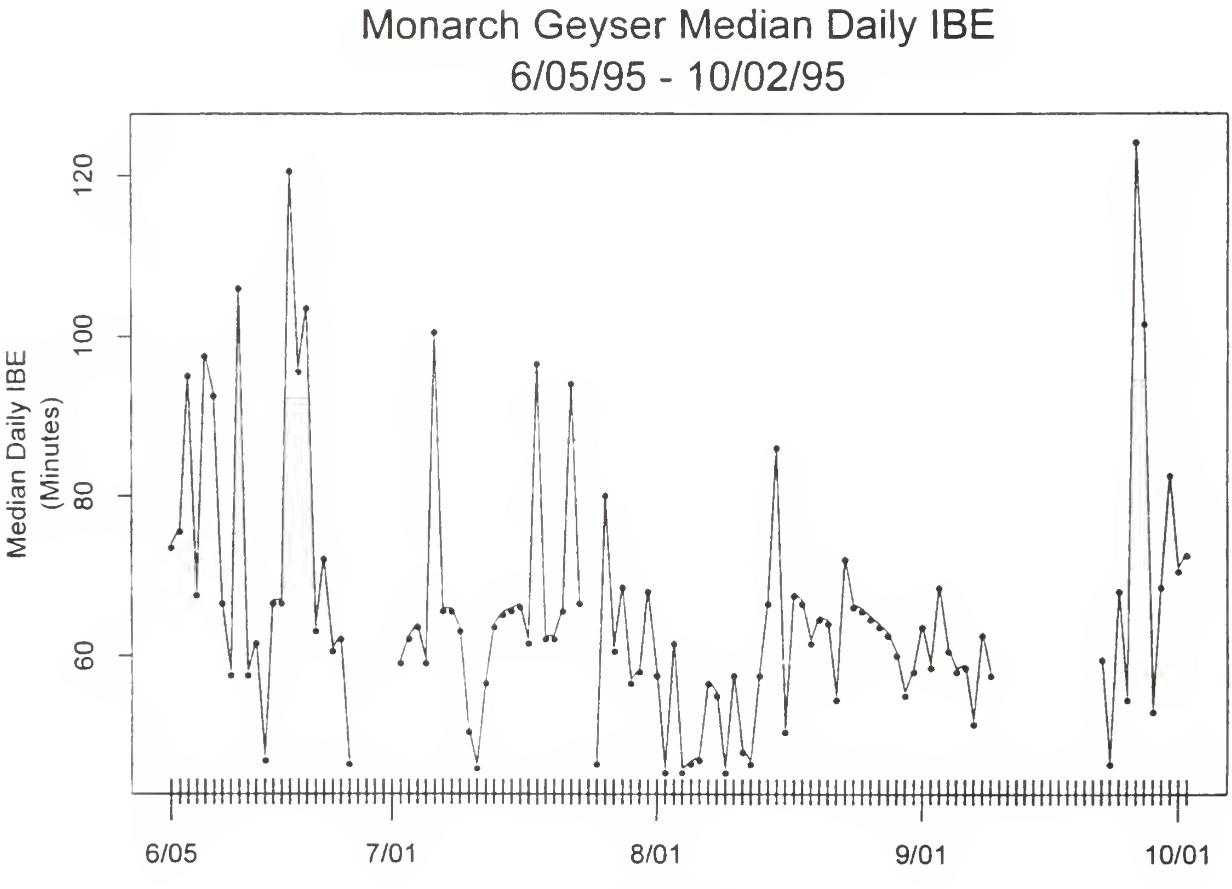
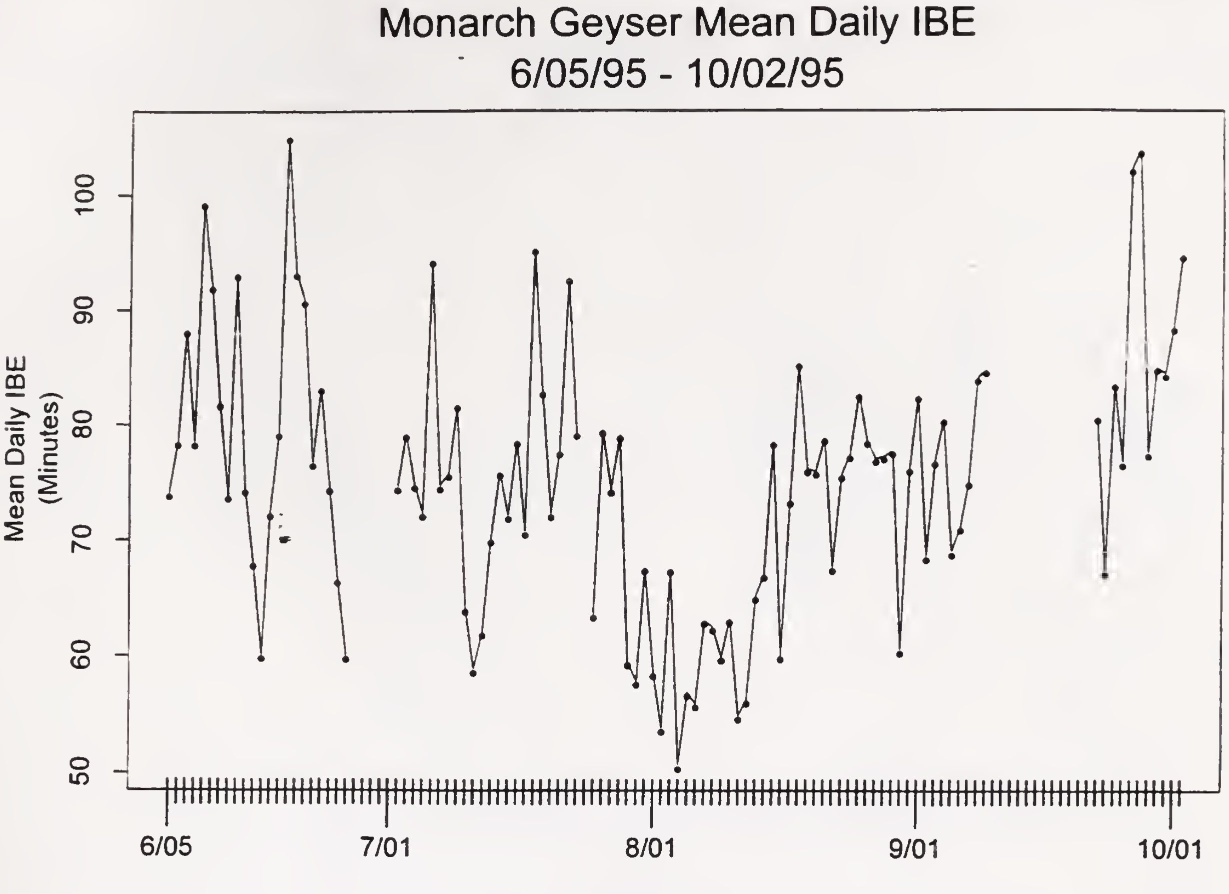
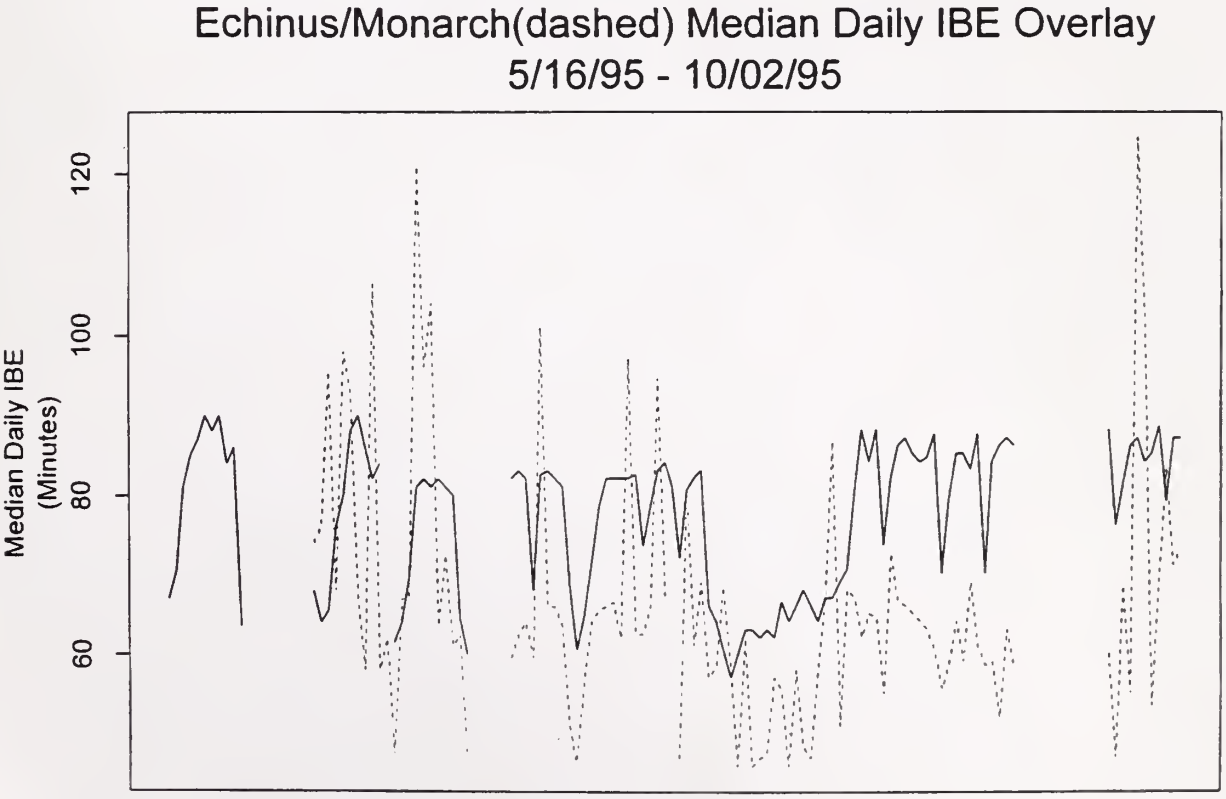


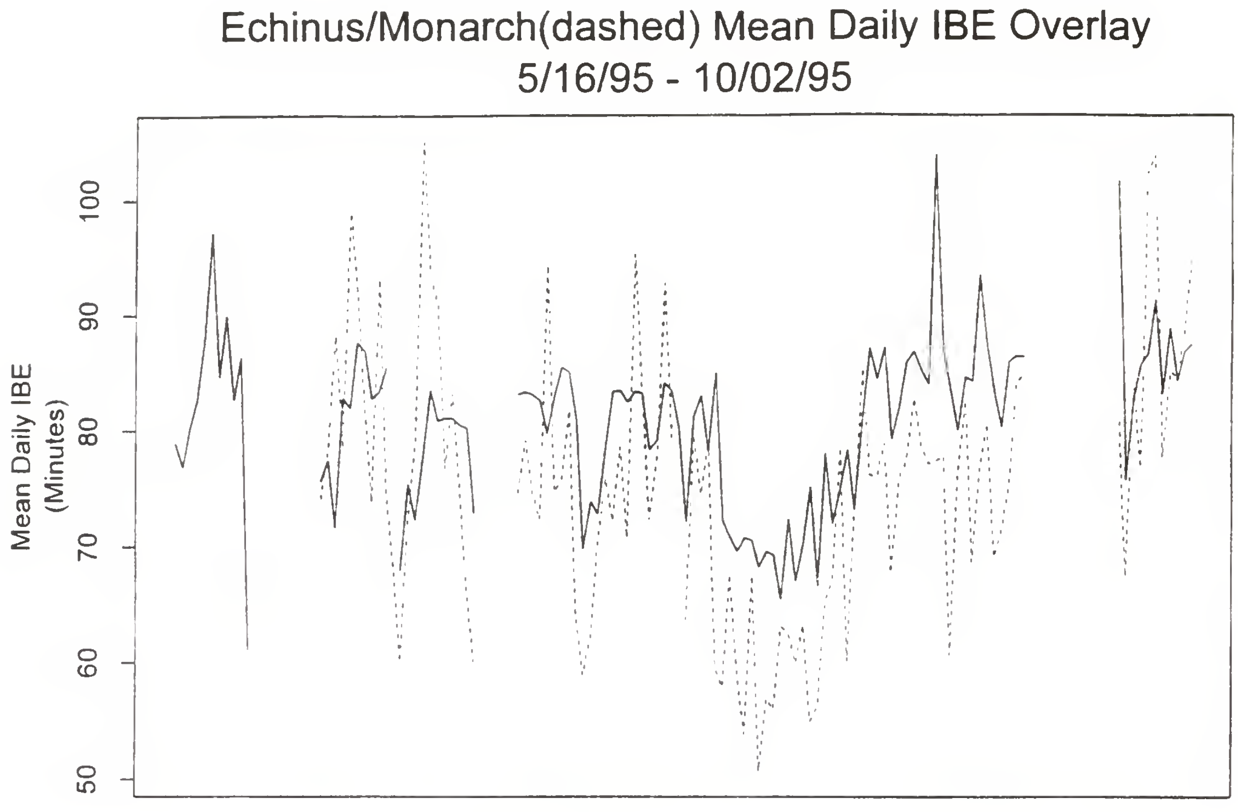
Figure M2



Date - 1995
Figure M3



140 Day Series
Figure E-M1



140 Day Series
Figure E-M2